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High-Alumina Rocks in Ontario

Resources and Process Technology

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High-Alumina Rocks in Ontario: Resources and Process Technology

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Cover photo inset: Mineral and chemical products from nepheline syenites include sands for the glass industry and aluminum oxide (alumina).

Note: This paper does not represent official policy and the views expressed herein are not necessarily the viewpoint of the Government of Ontario.

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Summary

High-alumina rocks (over 20% weight % Al_2O_3) of plutonic igneous origin are represented by major deposits in Ontario. Rock types in this category are predominantly anorthosites and nepheline-bearing syenites and gneisses. These rock types have been the subject of worldwide process research and commercial demonstration over many decades, and are currently mined in Canada, Norway and the U.S.S.R. (nepheline syenites) and in Finland (anorthosites). They have gained attention as raw materials for mineral and chemical products for two main reasons:

1. Exceptionally high feldspar ± feldspathoid mineral content; nepheline syenites and gneisses of interest contain 80 to 95% of these minerals, while anorthosite contains at least 90% feldspar by definition.
2. High alumina values in chemical composition; rock analyses often range upwards from 20% Al_2O_3, and can average up to 34% Al_2O_3 for some anorthosites.

The review of process technologies covers the methods in current industrial operations using anorthosites or nepheline-bearing materials and those that demonstrated technical viability in the extraction of products of commercial interest. The production of dimensional stone and crushed aggregates, which do not require metallurgical treatment, was specifically excluded from the review. Economic evaluations of the distinct processes were outside the scope of the terms of reference for the review.

Process research has demonstrated, from a bench-scale up to pilot operations, the technical feasibility of several options using high-feldspar, high-alumina sources to provide marketable products. Different process technologies: mineral beneficiation, lime sinter and acid leach, are already successfully employed in present-day operations in several countries to provide diverse products; the most recent operation was brought on stream in Finland in the 1980s.

Ontario is a long-standing and well-established supplier of mineral products from nepheline syenite for the glass and ceramic industries. The products, alkali feldspars combined with the feldspathoid nepheline as well as by-product magnetite, have been obtained by dry separation techniques of mineral beneficiation. Product development over the years, for both the Canadian and Norwegian producers of mineral grades, has focussed on fine grinding and classification methods for micronized filler and extender grades for paints, plastics and rubber manufacturing. This review of applied or researched process technologies has illustrated that further options for new or improved products from Ontario are available in the exploitation

of suitable deposits of nepheline syenite, nepheline gneiss or anorthosite in the province.

Processes for Mineral Products

No major changes in product requirements are foreseen for the dry-processed nepheline syenite grades that are available from Ontario. The low-value application of sandblasting may increase, principally at the expense of silica sand, in view of regulatory trends with respect to products containing free silica. There is no restriction on iron content of an abrasive for sandblasting use, and this may increase the range of selection of nepheline syenite deposits.

At the high-value end of the range for nepheline syenite products, further refinements in micronized filler grades may be possible by ultrafine grinding and classification. Some product expansion may be achieved with a future development of surface-modified fillers. Such products, surface-treated with coupling or wetting agents to improve their compatibility and performance in polymer resins, would require research into appropriate modifiers and the enhancement of filler properties.

Froth flotation techniques, in conjunction with magnetic separation, for the treatment of nepheline syenite merit further investigation in Ontario. The ability to separate non-magnetic deleterious minerals by wet processing can expand the choice of rock suitable for high-purity products. There is also potential for product innovation with the separation of a unique nepheline concentrate and feldspar fraction, offering broader product lines to the glass and ceramic industries. Furthermore, by-product yields could include corundum from certain deposits, in addition to magnetite by magnetic separation.

Anorthosites can be similarly treated by both dry and wet process routes in mineral beneficiation. Although not favoured as a flux in traditional ceramic manufacturing processes in comparison with nepheline syenite or other sodic/potassic feldspar products, anorthosite could act as a low-cost substitute for wollastonite in ceramics which are produced by the fast-firing process. The most appropriate applications would be floor and wall tiles and electrical porcelain, requiring low-iron anorthosite with a calcium content of between 7 and 10%.

Another potential application for anorthosite may be as a constituent in the manufacture of mineral wool. High-calcium anorthosites have a chemical composition that is reasonably close to the desired range, and the material could be a partial substitute for nepheline syenite and/or blast furnace slag.

Other potential uses for anorthosites include abrasives, welding fluxes, and as a flux in the delacquering of aluminum beverage cans. These applications, however, are considered to have limited potential or present technical problems to more widespread use.

Processes for Chemical Products

Acid Leaching

Anorthosites and nepheline syenites can be raw material sources of various industrial inorganic chemicals. Research and development has generally concentrated on the extraction of the higher alumina values found in high-calcium anorthosites, rather than the lower grades that are typical of nepheline syenites.

Sulphuric acid treatment of anorthosite is used in Finland for the commercial production of aluminum sulphate (alum). Utilization of a similar process in Ontario would be assisted by the ready availability of the mineral acid and by the commercial potential of calcium silicate, white silica powder and calcium sulphate by-products. The principal users of alum are in pulp and paper manufacture and water treatment, while the by-products have applications in cement production and as resin fillers.

Anorthosites vary greatly in their leaching behaviour with mineral acids; although pre-leaching techniques of melt-quench procedures are shown to be effective with poorly-responsive anorthosites, they provide a substantial cost penalty to the process. Research findings indicate that such measures can be avoided by the selection of ore with favourable mineralogical compositions, expressed variously as over 60% anorthite content of the rock or with a Si:Al ratio below 1.5:1. The processes developed for anorthosites by the U.S. Bureau of Mines (fluoride-assisted hydrochloric acid leach-gas sparging) or by Alcan Aluminium Limited in Canada (hydrochloric acid-calcium chloride leach-gas sparging) could be the basis for future process development as warranted by economic conditions. Such processes, although primarily designed for the production of cell-grade alumina, can also provide by-product silica for use as resin fillers or lead to the production of colloidal silicas and silica gels.

Nepheline syenites and anorthosites can also be starting materials for the production of synthetic zeolites. Feldspathoids such as nepheline are particularly amenable to acid treatment. Although a wide range of

zeolites can be synthesized, depending on factors of gel composition, nature of the reagents and conditions of crystallization, product engineering may develop suitable materials for niche markets.

Research into the bioleaching of feldspathoid minerals, such as nepheline, has not yet demonstrated encouraging product recoveries. Nevertheless, further investigation is required for a potentially low-cost, environmentally attractive process.

Alkaline Processes

Lime sinter processes are employed in the commercial production of alumina from nepheline-bearing ores in the U.S.S.R. Applicable to both nepheline syenites and anorthosites, sintering processes have very high energy requirements and use large quantities of limestone.

Alumina production based on a process similar to that developed in the U.S.S.R. would also provide large volumes of Portland cement (9 to 11 tonnes per tonne of alumina) as well as sodium carbonate (soda ash) and potassium carbonate. Although not presently considered as a competitive alternative in North America to Bayer-processed alumina for aluminum production, opportunities may be available for highly calcined alumina products such as tabular alumina. These products are in relatively short supply in North America and command prices considerably in excess of those obtained for cell-grade alumina for aluminum manufacturing. There are also ready markets for an Ontario source of soda ash and potassium carbonate materials. The marketing of large quantities of Portland cement would be a key factor in an assessment of the commercial potential of sinter processes in this region.

The direct use of unpurified ores, such as anorthosites and feldspathoid-bearing materials, is feasible in carbothermic processes that include both reduction and purification. This could present opportunities for cost reduction if less expensive feed than Bayer alumina can be used for aluminum or aluminum-silicon alloys and/or commercial by-products can be offered. In the case of the Norwegian Pedersen process, a market for iron concentrate would be needed to partially offset the cost of aluminum production.

Both acid and alkaline processes for the treatment of anorthosites and nepheline syenites can offer important suites of chemical products for industrial use. Table 1 lists the main feasible products that have been mentioned in the review of process technologies.

The North American market for alumina intended for aluminum production is currently supplied by established low-cost producers using bauxitic raw materials. Entry into this market segment, especially on a small scale, may not be a viable option. Good market opportunities may be available, however, for other alumina grades (e.g., tabular and refractory) as well as key by-products. It is likely that the potential commercial viability of any of such processes installed in Ontario will depend on the aggregated market for co-generated products.

High Alumina Rock Deposits in Ontario

A total of 22 anorthosite bodies and 13 occurrences of nepheline syenites (and rock types of close affinity) were selected for property-scale reports. The following guidelines for selection as targets of potential commercial interest were used:

1. Crystalline igneous bodies with a minimum chemical composition of 20 weight % of aluminum oxide (Al_2O_3)
2. Minimum total alkali content, defined as $Na_2O + K_2O + CaO$, of 12 weight %.
3. Compositional homogeneity for a minimum volume of 10 million tonnes.
4. In the absence of adequate chemical data, the mineralogical composition should be dominantly feldspars and/or feldspathoids that would meet the modal analysis required for unaltered rock. Deposits of low mafic mineral content would be preferred for consideration.

The syenites chosen for review occur in the Grenville Province of southern Ontario. There are several occurrences in the Superior Province to the north that may merit further attention, but they were generally qualified as secondary targets for reasons of heterogeneity, high mafic mineral content or inadequate characterization of the extension and mineralogy of these bodies. Syenite analyses generally show lower alumina values than that found in anorthosites, typically closer to the 20% Al_2O_3 cutoff mark used in this review. The presence of nepheline and corundum increases analyses of Al_2O_3 to between 23 and 27 weight %, particularly in the belt-type occurrences and the Blue Mountain deposit. The total alkali content in syenites is similar to that in anorthosites; whereas CaO dominates in anorthosites, however, Na_2O is the principal alkali in syenites, normally comprising two-thirds of the total alkalis.

Chemical analyses show alumina values for many of the anorthosite bodies consistently above 25 weight %; the highest alumina values (averaging between 27 and 29%) were noted from the Allsaw, Arnstein, Raganooter, Moon River, Percy, Bad Vermilion and Shawmere Anorthosites.

Ontario is the world's largest producer of nepheline syenite grades for glass, ceramics and filler applications

Table 1.
Feasible Products From Raw Materials Reviewed in This Publication

Mill Process	Rock Type	Feasible Products
Mineral Processing		
(a) Flotation with Separation	Nepheline Syenites	• Nepheline • Alkali Feldspars • Alkali Feldspars + Nepheline • Magnetite (minor) • Corundum (minor)
	Anorthosites	• Plagioclase Feldspars • Magnetite (minor)
(b) Dry Separation	Nepheline Syenites	• Alkali Feldspars + Nepheline • Magnetite (minor)
	Anorthosites	• Plagioclase Feldspars • Magnetite (minor)
Acid Processes	Nepheline Syenites and Anorthosites	• Aluminum Sulphate (Alum) • Calcium Silicates • Calcium Sulphates • Calcium Nitrates • Sodium Aluminates • Silica Gels • Zeolites • Alumina
Sinter Processes	Nepheline Syenites and Anorthosites	• Alumina • Calcium Silicates • Portland Cement • Potassium Carbonate • Sodium Silicates • Wollastonite • Zeolites
Direct Reduction	Nepheline Syenites and Anorthosites	• Alumina • Aluminum-Silicon Alloys

from its Blue Mountain deposit, using dry separation techniques of mineral processing for over 50 years. Other process technologies offer the prospect of different product lines, serving new consumer segments, by the treatment of nepheline syenites. Similar process options are also available for anorthosites. Major deposits of these rock types are well-known in Ontario, but often need improved geological characterization with respect to their product potential, particularly for chemical products. The economics of alternative processes and their primary commodity products should be monitored for developments that may lead to the commercial exploitation of a suitable high-alumina, high-feldspar prospect in Ontario.

1. Introduction

Ontario has been an established major producer of treated nepheline syenite products for over 50 years. Nepheline syenite is an alkalic alumino-silicate rock of plutonic igneous origin, although metamorphic processes have been advocated for the formation of some deposits.

Nepheline syenites are currently used in commercial applications primarily as fluxes in the glass and ceramic industries. They are also exploited as a source of alumina. Anorthosites are also plutonic igneous rocks which, although limited in appeal as fluxes, have generated interest for many decades as a source of alumina and other chemicals.

Nepheline syenites and anorthosites are represented by major deposits in Ontario. In addition to a shared mode of geological formation, they have been the subject of world-wide research for two main reasons:

- Their mineral composition is dominated by feldspar ± feldspathoid minerals; nepheline syenites of major interest contain 80% to 95% of these minerals, while by definition anorthosite contains at least 90% feldspar. Currently, this composition, in the case of nepheline syenite, provides a premium product in the markets for feldspathic materials.
- They have high alumina content, commonly ranging from 20% Al_2O_3 up to 34% Al_2O_3 (in anorthosites). This has made them an attractive target for both aluminum chemical producers and for research as alternate non-bauxite sources for alumina production.

The purpose of this review is three-fold:

a) to identify the principal deposits of this lithological category in Ontario that qualify as targets of potential commercial interest,

b) to document the international status of research and the operational technologies that are technically feasible for processing igneous rock types of a high feldspar/feldspathoid content, with particular consideration of applicability to Ontario resources,

c) to identify the product potential of investigative efforts.

Ontario is already a major supplier of beneficiated grades of nepheline syenite to the international markets in glass, ceramics and fillers. It is the intention of this review to draw attention to the technical options for product innovation and diversification by the exploitation of this special category of high-alumina rocks.

Terms of Reference

The high-alumina resources in Ontario to be identified in this review were categorized as follows:

1. Crystalline igneous bodies with a minimum chemical composition of 20 weight % of aluminum oxide (Al_2O_3).
2. Minimum total alkali content, defined as $Na_2O + K_2O + CaO$, of 12%.
3. Compositional homogeneity for a minimum volume of 10 million tonnes.
4. In the absence of adequate chemical data, mineralogical composition should be dominantly feldspars, feldspathoids or a combination that would satisfy the modal analysis required for unaltered rock. Bodies of low mafic mineral content would be preferred for consideration.

The review of selected process technologies was confined to those rock types identified as potential targets in Ontario. These were anorthosites, nepheline syenites and rock types of close affinity; volcanic deposits such as phonolites were not identified as provincial targets (under the guidelines of volume) and were consequently not included for consideration. The published literature, including patents, was searched for references to processes applicable to the target rock types as source materials, as well as materials of kindred mineralogy. Process technologies selected for inclusion in the review included all techniques in current industrial operations using anorthosites or nepheline-bearing materials and those that demonstrated technical viability in the extraction of products of commercial interest. Specifically excluded from the review is the production of dimensional stone or crushed aggregate, which does not require mineral beneficiation or other process treatments. The processes of interest yield products that are valued for their particular mineralogical composition and/or related chemical values. Actual or potential products for industrial use were identified, and their applications described in general terms, from the processes under review.

Assessment of the process technologies was limited to their technical feasibility or merit; economic evaluations were outside the scope of the review.

Methodology

The review of process technologies was based on a search of published technical literature and patents on a world-wide basis. The selection of technologies for inclusion in the review was based on consideration of technical feasibility at the stages of research, development and commercial demonstration.

The compilation of Ontario deposits was initiated by a search of the PETROCH database of lithogeochemical data for all samples with compositions of over 20% Al_2O_3. The PETROCH database includes all samples submitted by Ontario Geological Survey geologists for whole rock and/or trace element geochemistry between 1974 and October 1988. Continuing work included an extensive search through provincial and federal geological reports, university theses and scientific papers to identify further candidates for inclusion. The combined results of the literature and PETROCH searches identified 369 targets, including a range of rock types. Non-igneous rock types were eliminated by the terms of reference, and others did not meet the restrictions of consistency of composition and minimum volume of 10 million tonnes, e.g., volcanic units and dikes. The final selection of prospective bodies covered in the review was based on their qualifications with respect to the compositional guidelines for alumina and total alkali content as well as on considerations of overall size of the body, lowest possible content of mafic minerals and availability of data.

Examination of the literature revealed a fundamental problem with respect to the availability of data, in order to establish bodies of rock containing over 20% Al_2O_3. Sampling based on geological mapping is fundamentally different from economic sampling carried out in property evaluation. Sampling methods of mappers normally concentrate on characterizing rock types. Hence, geochemical sampling is commonly sparse and erratic, as opposed to the systematic sampling methods used during property evaluation by mining companies. Since Al_2O_3 and total alkali content have not previously been seriously considered an exploration target, regional sampling does not outline zones or units of consistently high Al_2O_3, CaO, Na_2O or K_2O compositions. Consequently the present literature provides insufficient data to characterize many of the possible targets.

Definition of Mineral and Rock Terms

General mineralogical terms are defined by Kerr (1977) and Deer, Howie and Zussman (1963). Currie (1976) provides a brief glossary of commonly used terms which have been used with reference to occurrences described in this report. The Glossary of Geology (Bates and Jackson 1987) is recommended for more thorough explanations of geological terminology. However, included here are descriptions of the fundamental terms used.

Mineral Terminology

Feldspar: There are many feldspar minerals. These are generally grouped on the basis of relative proportions of calcium (Ca), sodium (Na) and potassium (K) present or more specifically, on the proportions of the end members anorthite, albite and orthoclase. Figure 1 (Kerr 1977) graphically illustrates the compositional ranges in feldspar minerals. Different mineral names are given for the compositional ranges, where anorthite has the highest proportion of calcium, albite has the highest proportion of sodium and orthoclase has the highest proportion of potassium. The term plagioclase refers to the calcium-sodium solid solution series and alkali feldspar to the sodic and potassic end members.

The intergrowth texture of albite and potassium feldspar is known as perthite or microperthite depending on the scale of exsolution (Kerr 1977). This texture is commonly present in the feldspars in syenites.

Trachytoid texture is a term often applied to feldspathic rocks (including syenites) where feldspars have a parallel or subparallel disposition (Bates and Jackson 1987).

In general, Ca-rich plagioclase occurs predominantly in more mafic rocks (less than 5% quartz) particularly anorthosite and gabbro. Alkali and perthitic feldspars occur more frequently in felsic rocks particularly granites and syenites.

Feldspathoid: A mineral which in general terms

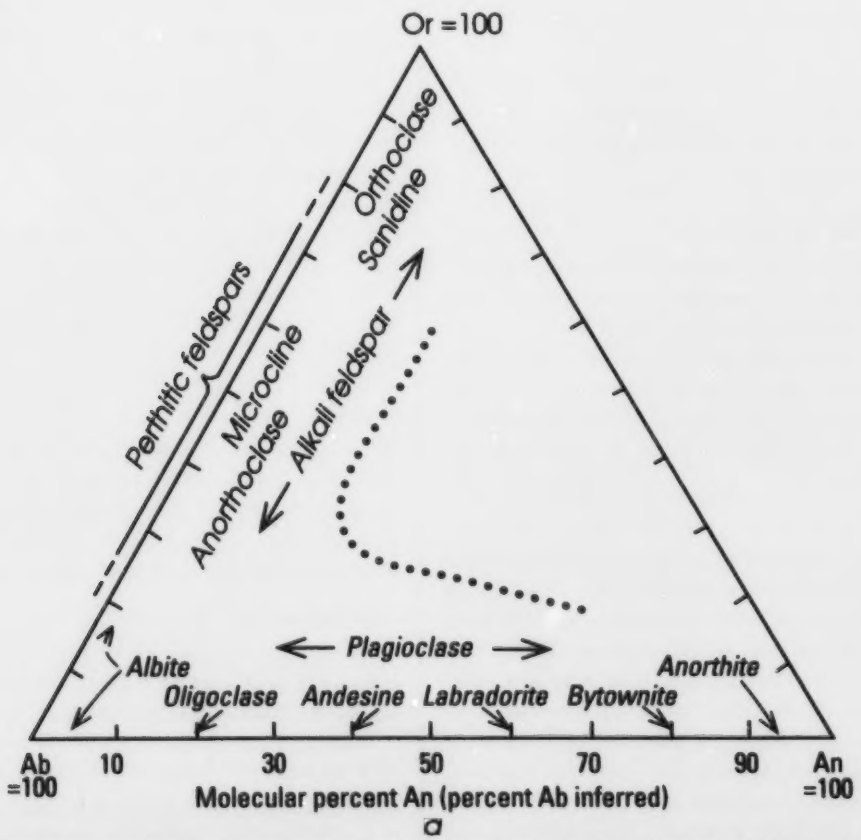

Figure 1. Distribution of the Feldspars in the Ternary System OR-Ab-An ($KAlSi_3O_8$-$NaAlSi_3O_8$-$CaAlSi_3O8$). Source: Kerr 1977.

can be considered a silica deficient feldspar (Deer et al. 1963) belongs to the group of feldspathoid minerals. Minerals belonging to this group (although not all technically classified as feldspathoids) include nepheline, sodalite, cancrinite, leucite, hauyne and melilite. These minerals are characteristic of nepheline syenites, phonolites, and other silica-poor alkalic igneous rocks.

Nepheline: is an Na_2O- and Al_2O_3-rich, colourless (or white to grey), feldspathoid mineral common to silica-undersaturated alkalic rocks, particularly syenites. Chemical analyses of nepheline average 33 weight % Al_2O_3. Nepheline is often associated with alkali feldspars (Deer et al. 1963). Within the Bancroft Terrane, nepheline most commonly occurs in gneisses, in widely variable proportions. Sodalite and cancrinite are common alteration products of nepheline, typically occurring along fractures. Textures such as nepheline enclosing rounded feldspars and intricate albite-nepheline intergrowths are characteristic of the Bancroft Terrane rocks (particularly York River area: (Tilley 1958). Large crystals of nepheline, over 5 cm in length, are reported in some nepheline pegmatites of the Bancroft Terrane (Hewitt 1960).

Hydronephelite: is a zeolitic alteration of nepheline (i.e., hydrous sodium calcium aluminum silicate (Kerr 1977)), most commonly occurring as the varieties: thomsonite and/or natrolite.

Rock Terminology

Mafic: applies to compositions of both rocks and minerals. A mafic rock contains over 35% mafic minerals. Mafic minerals are usually those which contain Fe and/or Mg as essential components, e.g., all pyroxenes, amphiboles, olivines, biotite, etc. With respect to industrial minerals and Al_2O_3, CaO, Na_2O and K_2O content, the lowest possible mafic component is desirable.

Anorthosite

Anorthosite: is defined as an igneous, intrusive rock composed of at least 90% plagioclase, of oligoclase to anorthite composition, with the remaining 10% consisting of: clinopyroxene, orthopyroxene and olivine (Streckeisen 1976). Biotite and scapolite are commonly abundant in metamorphosed anorthosites.

Anorthosite occurrences in Ontario display a wide variety of sizes, compositions and textures. Massive, relatively homogeneous anorthosite bodies are known to occur in the Grenville Province. Anorthosite in the Superior Province is more commonly associated with layered mafic intrusions, where gabbro is a significant component of the intrusion. Sizes range from the narrow tectonic slivers common to the Parry Sound area, covering only a few km^2 to large bodies hundreds of km^2 (e.g., Shawmere Complex).

Anorthosite, when associated with layered mafic intrusions (e.g., Lac des Illes Intrusion), occurs as semicontinuous, centimetre to metre scale, bands interlayered most commonly with gabbro and occasionally pyroxenite. The proportion of anorthosite in these bodies can very from around 10% to 90%. Due to the sporadic distribution of the anorthosite in these bodies, however, they represent secondary targets and are not described in detail in this report.

Large anorthosite bodies in the Grenville and Superior Provinces commonly contain Al_2O_3 in excess of 20 weight %. Prospective bodies were chosen on the basis of availability of data and overall size of the body.

Gabbroic anorthosite: is applied to rocks intermediate between gabbro and anorthosite, with a higher proportion of mafic minerals than an anorthosite, i.e., 10 to 22.5%.

Anorthositic gabbro: is applied to a rock with a composition intermediate between anorthosite and gabbro, with more plagioclase than a gabbro and between 22.5 and 35% mafic minerals.

Gabbro

Gabbro: is used in this report to mean an igneous, intrusive rock, composed of at least 35% and up to 65% plagioclase (typically labradorite to bytownite composition), clinopyroxene as the major pyroxene, and less orthopyroxene and olivine. Hornblende and biotite are often major constituents of metamorphosed gabbros.

Gabbro is commonly associated with anorthosites (and pyroxenites) in layered intrusions (Streckeisen 1976). Total alkali content and usually alumina content in gabbroic rocks is much lower than that of anorthosites and syenites, due to the higher proportion of mafic minerals in gabbros, and for this reason they are not considered in this review.

Syenite

Syenite: is defined as an igneous, intrusive rock composed of at least 65% alkali feldspar, and less than 5% quartz. Plagioclase and mafic minerals make up the remaining mineralogy. A leucocratic syenite can contain up to 30% mafic minerals, and a mesocratic syenite will contain more than 30% mafic minerals (e.g., mesocratic nepheline syenite of the Callander Bay Complex). The term alkali syenite is often used to describe a rock where alkali feldspars constitute

90% or more of the rock, and plagioclase compositions are An_{0-40}, where plagioclase is present. Syenites such as the Otto Stock, Lebel Stock, McElroy Stock of the Superior Province and the Gawley Creek, Mount Moriah, Skootamatta, Burns Lake and Mount St. Patrick Syenites of the Grenville Province containing neither quartz nor nepheline is considered saturated. Oversaturated rocks contain modal quartz, incompatible with the presence of nepheline and therefore representing less attractive targets since Al_2O_3 content is limited. Undersaturated rocks contain modal nepheline, and these bodies, where they contain less than 10% mafic minerals, represent more prospective Al_2O_3 and $CaO+Na_2O+K_2O$ targets.

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2. Review of Process Technologies

Historical Background

Nepheline-bearing rocks and anorthosites are currently being exploited commercially for beneficiated mineral products or chemical derivatives in Canada, Norway, Finland, the U.S.S.R., France and Germany.

Canada was the Western World's first producer of feldspar-nepheline concentrates with the start of operations in Ontario over 50 years ago. Considerable interest for new fluxes with improved specific properties had developed in the glass and ceramic industries in North America by the late 1920s. Important advances in magnetic separation techniques, at that time, opened up the opportunity to develop low-iron nepheline syenite products from the Blue Mountain deposit in Ontario's Methuen Township, 175 km northeast of Toronto. The first commercial shipments were made in 1935; ore was barged to a mill at Lakefield, 40 km from the quarry, and treated material was shipped to Rochester, New York State for further grinding and distribution. A mill for finished products was located at the deposit in 1946, and was replaced on an adjacent site by a new plant in 1956. A second company commenced separate quarrying and processing operations at the northeastern end of the same deposit in 1956. Today the quarry operations for the entire deposit and the two processing plants are owned and operated by Unimin Canada Ltd., with an estimated annual production capacity of 800,000 tonnes for a combination of glass, ceramic and filler grades.

Similar markets in Western Europe are largely supplied by nepheline syenite from northern Norway. Evaluation of a high-quality nepheline syenite deposit on the island of Stjernøy, about 50 km southwest of Hammerfest, in the 1950s led to the establishment of a process plant and commercial shipments began in 1961. Although Stjernøy is located approximately 400 km north of the Arctic Circle, it is accessible to shipping on a year-round basis because of the moderating effect of the Atlantic Ocean's Gulf Stream. The mine and plant are operated by Norsk Nefelin, a subsidiary of Elkem A/S, and annual production capacity is around 300,000 tonnes.

The evaluation of a nepheline syenite deposit at Canaan, 40 km northeast of Rio de Janeiro in Brazil, reached the level of commercial demonstration with the pilot production of low-iron glass-grade products in 1980-1981, but no further developments have been noted to date.

Although there are numerous other world-wide occurrences of nepheline syenite that have been evaluated for glass and ceramic grade potential, they have generally proved unacceptable because of consider-

able variations in chemical composition and/or an over-abundance of iron-bearing or other detrimental accessory minerals, notably refractory minerals, not amenable to beneficiation. Most of Ontario's nepheline syenites and gneisses in the Grenville Province have been the subject of such evaluations in past decades; two U.S. companies processed nepheline syenites from the Bancroft and Gooderham areas between 1937 and 1942, for example, but the products proved to be unacceptable. One Ontario deposit that has received particular attention has been the Bigwood-Rutter nepheline syenite, well located with respect to rail facilities and to deep-water harbour facilities at Georgian Bay. Exploration and beneficiation tests, most recently in the early 1980s, demonstrated that it could meet maximum product specifications of 0.35% Fe_2O_3 equivalent for glass grades other than flint (colourless) glass.

Phonolites, the volcanic equivalent of nepheline syenites, are currently worked in France and Germany, and were formerly exploited in Czechoslovakia. Their fine-grained textures do not make them amenable to superior upgrading and product grades with 2 to 5% Fe_2O_3 are used in coloured glass and ceramics. Phonolites have not been identified as a significant resource in Ontario and are excluded from further discussion in this review.

Anorthosites are generally not recognized as attractive fluxes in the traditional manufacturing processes for glass and ceramics, although there may be new opportunities in the developing technologies of short-firing cycles in ceramics production. The melting points of the dominant calcium feldspars in anorthosites are characteristically in excess of 1500°C; this contrasts with the popular sodium and potassium feldspar fluxes, which fuse within the range of 1100° to 1200°C. Calcium compounds also generally decrease the firing range of a ceramic body.

The alumina content of nepheline-bearing rocks and anorthosites has attracted attention for many decades. These resources have been the subject of considerable study as alternatives to bauxite, the almost universal ore for alumina and aluminum production for over 100 years. In spite of the dominance of the Bayer process for the production of alumina from bauxite (and the Hall-Heroult process for the production of aluminum from alumina) there has been considerable research and development for alternatives to both bauxite and the Bayer process for many years in more than 20 countries, with greater activity in times of political or economic restraint towards the use of bauxite. Several countries such as Italy (phonolite) and Norway (anorthosite) either experimented with or utilized substitute raw materials during the Second World War. The Soviet Union, which has little bauxite, produces alumina from nepheline syenite or nepheline concentrates today. It has been a subject of ongoing interest in Canada, which is one of the world's major aluminum producers but has no domestic source of bauxite. The Bayer process is not suitable for nepheline or feldspar minerals, because the digestion process utilizes caustic soda, which reacts with the silicon content of alumino-silicate minerals to form insolubles, resulting in the loss of both alumina and caustic soda (Bliss 1976).

Nepheline concentrates from apatite mines at Khibiny Mountain in the Kola Peninsula of the U.S.S.R. were successfully tested for use in producing alumina before the Second World War. Industrial production of alumina from these concentrates, however, did not start until 1951 at a plant in Volkhov, about 110 km east of Leningrad. A second alumina plant at Pikalevo near Volkhov, began using the concentrates in 1959. The Khibiny Mountain nepheline syenite body is characterized by an unusual suite of rarer elements and rocks of more extreme composition and is valued for its apatite and rare earth mineral content. The nepheline concentrates are not derived from the nepheline syenite per se, but from an associated apatite-nepheline rock (Allen and Charsley 1968). Alumina is also produced in the U.S.S.R. from the nepheline syenite deposit at Goryachegorsk in the central Siberian territory of Krasnoyarskiy Kray. Ore mined in this operation, developed in the mid-1960s, is shipped about 200 km to the large alumina plant of Achinsk, which was also reported to be using bauxite ores for a portion of its production.

Research, development and commercial demonstration for the extraction of alumina from feldspathic rocks has included work in Norway, Italy, U.S.A. and Canada. Acid processes were used to extract alumina from leucite-nepheline phonolites in Italy between 1925 and 1943. Experiments on the acid treatment of anorthosite were conducted in Norway during the Second World War, as well as by the Pedersen carbothermic reduction process. In Canada, tests were reported as far back as 1912 to extract alumina from finely-ground nepheline syenite from the Bancroft area of Ontario (Nicholson 1940). Feasibility studies with the same objective were also undertaken in 1942, using Ontario nepheline syenite, by the American Nepheline Corporation, the Aluminium Company of Canada and the Bureau of Mines, Ottawa (Bliss 1976). In the U.S.A., a 45 tonne per day alumina pilot plant was operated in 1951-1952 by the U.S. Bureau of Mines, based on an anorthosite-lime sinter process.

Although the process functioned well, Kvande (1987) reported that operating costs were high and that the alumina product had high silica and other oxide impurities.

During the 1970s, several major aluminum producers re-assessed the potential resources and processes for domestic non-bauxite sources of alumina. In Canada during this period, experimental investigations were carried out by Alcan Aluminium Ltd. and by the Federal Government's Canadian Centre for Mineral And Energy Technology (CANMET). Ontario deposits sampled for laboratory tests during this period were the Bigwood-Rutter nepheline syenite and the anorthosite bodies of Shawmere, Parry Island, Whitestone, Wilkinson and River Valley. These deposits are described further in Chapter 3.

Virtually all of the chemical process investigations mentioned above have focussed on the objective of producing a pure alumina to compete with that obtained from bauxites by the Bayer process. Although the contribution of by-product values was recognized and demonstrated in U.S.S.R. operations, laboratory trials did not generally explore the potential for a suite of commercial-grade products other than cell-grade alumina. Such an approach by Kemira Oy in Finland in their research work on anorthosite led to the commercial development of a process for chemical products in the 1980s, primarily aluminum sulphate for pulp and paper and water treatment applications as well as a precipitated micronized silica product.

Current world-wide operations for the exploitation and treatment of anorthosites and nepheline-bearing rocks, excluding those for aggregates or dimension stone products, are listed in Table 2.

The following review of process technologies that have been employed or investigated in the treatment of anorthosites and nepheline-bearing rocks covers four main types of processes. They are those of mineral beneficiation, acid leach, sinter processes and direct reduction.

Processes For Mineral Products

Blue Mountain Nepheline Syenite, Canada

The deposit in Methuen Township in southern Ontario crops out as an elongate body 8000 m in length and up to 2500 m in width. The medium- to fine-grained rock typically contains nepheline (20 to 25%), albite (48 to 54%) and microcline (18 to 23%). Characteristic accessory minerals are magnetite (0.2 to 0.6%), biotite (up to 4%), hornblende (up to 3%), muscovite (up to 2%) and pyroxene. Other minerals in minor amounts include garnet, corundum, zircon, calcite, apatite and titanite. Up to six mineralogical zones of nepheline syenite have been distinguished and are largely classified by the predominant mafic minerals. Most of the mining has been conducted in the biotite zone, which is a light grey, medium-grained rock with magnetite and biotite as the principal accessory minerals and calcite in minor amounts.

Production of nepheline syenite at Blue Mountain follows typical open pit quarry operations to produce crusher run material. This is reduced in a primary jaw crusher and a secondary cone crusher and transferred to a surge bin. Material is recovered from the surge bin and passed through a rotary dryer to remove surface moisture and then to a storage bin. Material from the storage bin is screened; the +3/16 inch material is processed in a cone crusher or an impact crusher while the -3/16 inch material is fed to a series of double deck screens. Minus 3/16 inch, +30 mesh material is passed through roll crushers for further reduction. Minus 30 mesh material is fed to low intensity magnetic drums and screens and then to high intensity dry magnetic separators. Discharge from the separators is sold as glass grade nepheline syenite. Magnetite collected from the magnetic drums is sold as a by-product. Ceramic and filler grades of material are ground in pebble mills operating in closed circuit with air classifiers. Figure 2 provides a flow sheet for the operations of the main Nephton plant. The second plant's operations are similar. The operations produce high- and low-iron glass and ceramic grades of nepheline syenite, a range of grades for the filler and extender markets and by-product magnetite. Currently there is no production of surface treated grades for specialty filler and extender applications, although research has been conducted on the development of such grades.

Table 2.
World Mining Operations of Anorthosite, Nepheline Syenite and Phonolite
(excludes construction aggregates, dimension stone)

Location	Mining Organization	Rock Type	Product Output (est). Tonnes/Year	Primary Product Use
CANADA				
Methuen Township Ontario	Unimin Canada Ltd.	Nepheline Syenite Products	650,000 Feldspathic	Glass, Ceramics Fillers
NORWAY				
Stjernøy Alta Fjord	Norsk Nefelin, Division of Elkem A/S	Nepheline Syenite Products	250,000 Feldspathic	Glass, Ceramics Fillers
FINLAND				
Lapinlahti (Mine) Harjavalta (Plant)	Kemira Oy	Anorthosite	100,000 Aluminum Sulphate	Pulp & Paper Water Fillers, Cement
GERMANY				
Brenck (Mine) Eifel (Plant)	Kali-Chemic AG	Phonolite	60,000 Feldspathic Products	Glass, Ceramics
FRANCE				
Roche en Regnier Haute-Loire District	Société de Exploitation de Sables et Mineraux (SAMIN)	Phonolite	130,000 Feldspathic Products	Glass, Ceramics
U.S.S.R.				
Khibiny Mountain Kold Peninsula (Mine)	State-owned	Nepheline Syenite		
Volkhov, nr. Leningrad (plant)	State-owned		50,000 * Alumina	Aluminum Mfg. Alumia and Alkali Chemicals, Cement
Pikalevo, nr. Leningrad (plant)	State-owned		200,000 * Alumina	Aluminum Mfg. Alumiina and Alkali Chemicals, Cement
Goryachegorsk, Central Siberia (mine)	State-owned			
Achinsk, (plant) Central Siberia	State-owned		800,000 * Alumina	Aluminum Mfg. Alumina and Alkali Chemicals

Note: * Estimated Capacity

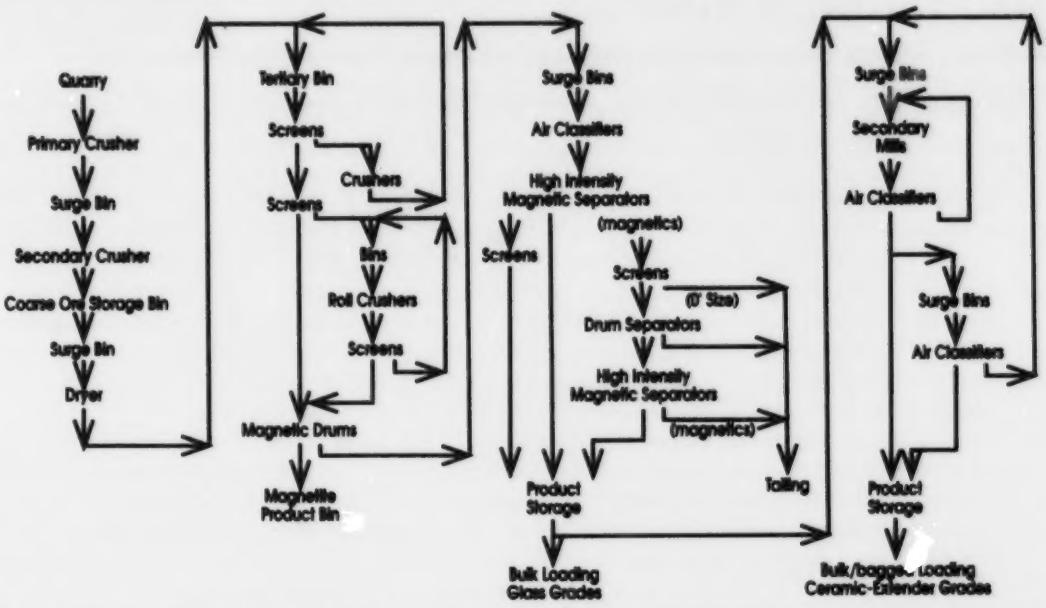

Figure 2. Production Process for Mineral Products from Blue Mountain Nepheline Syenite, Ontario (Nephton Plant) (from Minnes et al. 1983).

Stjernøy Nepheline Syenite, Norway

The deposit lies on the island of Stjernøy, which is near the northern tip of Norway. The lenticular surface outcrop of the body in 1700 m in length and up to 300 m in width.

The medium-grained, light-coloured rock is characterized by a uniform grain size. The major components are perthite (56%) and nepheline (34%), with minor plagioclase, clinopyroxene, hornblende, biotite, sphene and magnatite. Two main rock facies have been distinguished chiefly on the basis of the dark mineral contents; the biotite type contains 2.5 to 6.0% biotite as the main mafic material, whereas the hornblende type is characterized by 0.3 to 2.5% hornblende and 0.2 to 1.2% sphene. Corundum and zircon are minor components of both types (Geis 1979).

The processing plant and support facilities for the underground mine are located around Lillebukt Inlet. Ore is trucked to a jaw crusher where it is reduced to -4 inch, and then passed to a 4-foot standard cone crusher for reduction to -1.5 inch. Material from the cone crusher is stored in a 2500 ton underground bin or a 250 ton surface bin.

Ore is transferred to the processing plant from the storage bins by conveyor. It is passed over a single deck screen where the oversize material is put through a short head cone crusher and the -3/8 inch stone passes to a rotary drum dryer. From the dryer the ore is subsequently processed through a series of double deck screens, roll crushers, drum magnets and a single deck screen. At this point 90% of the nepheline syenite has been reduced to -30 mesh. The -30 mesh material is stored in a silo and withdrawn for processing through magnetic separation circuits. The material then passes over a series of screens where the remaining +30 mesh material is removed. The oversize material is processed in a pebble mill. Undersize material passes through an air classifier with the oversize being placed in glass grade product bins and the undersize material processed in the pebble mill for production of ceramic and filler grades.

Discussion

Dry separation processes have been adopted at Blue Mountain in Canada and at Stjernøy in Norway. The primary purpose is to produce a low-iron feldspar-nepheline concentrate to meet the specifications of the glass and ceramic industries and the filler markets. The relative homogeneity of the ore, general lack of rarer minerals and amenability to liberation and removal of iron-bearing constituents, attaining 1.0% maximum Fe_2O_3 (total iron equivalent) at minus U.S. 30 mesh, distinguishes both deposits from almost all the nepheline syenites evaluated to date by similar processing techniques.

Table 3 shows typical ore and low-iron product analyses for Blue Mountain and Stjernøy. They are

Table 3.
Comparative Analysis of Nepheline Syenite and Feldspar Commercial Production

	Blue Mountain Nepheline Syenite Ontario, Canada			Stjernøy Nepheline Syenite Norway			Spruce Pirie Alaskite N. Carolina, U.S.A.	
	Typical[3] Ore	Selected Products Glass Grade 340	Ceramic Grade A-400	Typical Ore[2]	Selected Products[2] Glass Grade	Ceramic Grade	Selected Products[1] Glass Grade f20	Ceramic Grade NC
SiO_2	59.4	59.9	60.7	52.4	55.9	56.0	68.0	68.1
Al_2O_3	23.0	23.5	23.3	23.7	24.2	24.2	19.0	18.5
Fe_2O_3*	2.4	0.08	0.07	3.0	0.10	0.12	0.07	0.07
CaO	0.6	0.6	0.7	2.5	1.3	1.2	1.9	1.6
MgO	0.6	0.1	0.1	0.2	tr	tr	tr	tr
Ma_2O	9.5	10.2	9.8	7.8	7.9	7.8	7.2	7.0
K_2O	4.9	5.0	4.6	8.1	9.0	9.1	3.8	4.0

*Iron expressed as ferric oxide

Sources: 1. Company Literature
2. Geis (1979)
3. Minnes et al. Blain (1983)

readily distinguished in chemical analysis on the basis of different Na_2O:K_2O ratios. An analysis of a typical feldspar product from North Carolina, U.S.A., which competes in many of the same uses as nepheline syenite, is also included in the table. This table illustrates the relatively high soda and potash contents in nepheline syenites, which provides special appeal to the glass and ceramic industries because of lower fluxing temperatures, as well as the higher alumina values.

The higher alumina and alkali content of nepheline syenite per unit weight in comparison with other competitive feldspathic products is reflected in unit prices. The selection of material by consumers depends on factors such as delivered cost, availability and priority; variability in the raw material is also a major consideration in batch formulations by consumer industries. Typical specifications for nepheline syenite products by different manufacturers of low-iron container glass and of glass fibre are shown in Table 4, illustrating tight chemical specifications.

Table 4.
Chemical Specifications For Glass-Grade Nepheline Syenite Products

	Container Glass Specification (by weight)	Glass Fibre Specification (by weight)	
	Low-iron Grade	Minimum	Maximum
SiO_2	0.50%	59.0	61.0
Fe_2O_3	0.10% maximum		0.5
Al_2O_3	0.50%	22.5	23.3
CaO	0.50%		1.5
Na_2O	0.50%	9.5	10.1
K_20	0.50%	4.7	5.3
Cr_20_3	0.0010%		
MgO			0.3
P_2O_5			0.01
As_2O_3			0.01
S			0.01
Fe (metallic)			0.005

In the case of container glass manufacturing, which is the largest market segment for nepheline syenite products in Europe and North America, it can be seen that chemical specifications for the major oxides are generally considered as tolerances rather than absolute limits. Strictly limited by specification are those minor constituents considered to be deleterious; this includes iron and chrome (visible colouration in flint glass), as well as refractory minerals, generally of +40 to +60 mesh, that will not dissolve in standard glass furnace operations, such as zircon, spinel, chrome, sillimanite, kyanite, andalusite and cassiterite.

Glass-grade feldspathic products are typically -30 mesh to -50 mesh (+200 mesh); ceramic grades are -200 mesh or finer and the filler grades extend to a fineness of 2 µm in average particle size.

Wet separation processes are employed by the majority of European and North American feldspar producers using froth flotation techniques, often in conjunction with magnetic separation. A trial in the 1940s to float nepheline from the other rock constituents of the Blue Mountain syenite was noted in the literature, but no results were published. The wet process route may merit renewed investigation in the treatment of nepheline syenite for the following reasons:

a) The feasibility of separating out weakly- or non-magnetic deleterious minerals may extend the choice of material available for designation as ore for glass and ceramic grades.
b) The separation of a nepheline concentrate and a feldspar fraction may present a significant expansion of product range. Nepheline has a theoretical Al_2O_3 composition of 34.8% and a high sodic content; separation would introduce a unique higher-alumina nepheline product as well as a feldspar product with an Al_2O_3 level comparable to the specifications for competitive feldspathic products in the existing marketplace.
c) Minor by-products, such as corundum, could be obtained from some deposits. This would be in addition to the recovery of magnetite by magnetic separation.

Mineral Product Uses

While the distribution of applications varies from country to country, about 85 to 90% of all feldspars and nepheline syenites in the market economy countries are consumed in the glass and ceramics industries, about 55% for glass and 30 to 35% for ceramics. The remaining 10 to 15% is distributed among several more "value-added" applications including fillers in paints, plastics and rubber.

Glass

Glass manufacturing and its principal segments, container glass, flat glass and glass fibre, is the major consumer of nepheline syenite by volume. Nepheline syenite adds alumina to the glass batch, which acts as a stabiliser and improves the durability of the finished product, and the contained alkalis are a useful fluxing aid to lower the melting temperatures. Alumina requirements are of the order of 1.5 to 2.0% Al_2O_3 in container and flat glass, and can sometimes be as high as 15% in specialty glass fibres.

Nepheline syenite has captured a large percentage of the glass market that can be reached, at delivered prices competitive with alternative alumina sources. It has a higher alkali-alumina ratio than feldspar and a lower fusion point; consequently less of the material is needed to provide the same amount of alumina and to produce the same fluxing action. This leads to a saving in energy costs as well as raw material costs in manufacturing.

The higher alumina content of nepheline syenite also has some effect on its use in flat glass manufacture. Glass melting tanks used in flat glass manufacture are generally much larger than those used for container glass or glass fibre manufacture. The larger size of the tanks means that materials in the glass batch must disperse and homogenize in a much larger volume. The higher alumina content of nepheline syenite means that it does not dissolve as quickly as feldspar, and thus longer heating times are required. Because of the higher alumina content, less syenite is required to achieve the same alumina level. However, this means that homogeneous distribution of the syenite in the batch is more difficult. Finally, the higher viscosity of the alumina impedes its fluid distribution in the melt. Solutions to these problems are available, but involve some changes to plant equipment and operating conditions. Given the ready availability of alternative materials, the potential advantages of nepheline syenite in flat glass manufacture are reduced. As a consequence, nepheline syenite has proportionately greater use in container glass and glass fibre manu-

facture than flat glass manufacture in North America.

The consumption of materials in glass fibres, principally for insulation products, is tied to cyclical markets in construction; nepheline syenite remains an important contributor to this well-established manufacturing sector.

Nepheline syenite faces downward pressures, however, in its utilization in container glass manufacture, which is still the principal consumer segment for feldspathic materials in the glass industry. These pressures include the following trend:

- The increase in the use of plastics, especially PET, HDPE, and PVC containers for a wide variety of materials previously packaged in glass. Metal and paper packaging materials have also had a significant impact on the demand for glass packaging materials.
- Increased recycling of container glass, resulting in reduced demand for fluxes. The use of cullet (scrap glass) may reach up to 25% in glass batch formulations.
- An increasing trend in the use of lightweight container glass, thereby reducing total glass batch requirements.
- Increased competition from blast furnace slags as a source of alumina and some alkalis.

Overall, North American consumption of nepheline syenite in the glass industry will continue to face pressure due to changes in packaging materials. Technologies need to be developed to produce stronger, lighter weight glass containers to compete on a cost/weight basis with plastics, aluminum, and paper. Such developments may halt the decline in container glass production. Research is also required in the development of processes to accommodate the use of nepheline syenite in flat glass production.

Ceramics

Feldspathic materials have been an essential flux in ceramic formulations for hundreds of years, and nepheline syenite is now an important player in this highly competitive but stable market.

The fluxes used in the ceramics industry include feldspar, nepheline syenite, feldspathic pegmatites, Cornish stone, aplite, eurite, and manufactured feldspathic fluxes. All the materials are ground finer than 200 mesh and must be free of calcite, which would yield CO_2 upon firing. The quality requirements for feldspathic ceramic fluxes primarily relate to particle size and size distribution, and the level of impurities. Substances emitting CO_2 such as calcite, cancrinite, and sodalite must be controlled at very low levels. Agents such as iron which lead to discolouration must be kept at a low level of 1% or less. The presence of refractory grains such as corundum must be minimized, as must fluorite which has a detrimental affect on the vitrification process.

The fluxing action of a feldspathic material depends on its free silica content, its alkali content, the ratio of Na_2O and K_2O, and the composition of the clay body into which it is introduced. In general, the greater the alkali content of the feldspathic material, the greater the fluxing action and the lower its melting point. Accordingly, the amount and type of material used varies with the type of ceramic being produced. Feldspathic material generally comprises 15 to 35 weight % of the body (and 30 to 50% of the glaze) in whiteware, pottery, tile, sanitary ware and other ceramic products (Clarke and Griffiths 1987).

Feldspathic materials are sold on the basis of fluxing units, which are defined as the total of Al_2O_3 + alkali oxides. Thus nepheline syenite, with its higher alumina content and reasonable alkali oxide content, has the highest fluxing unit content and commands a higher price than a typical soda feldspar on a per unit basis, even though the syenite may sell for less on a per tonne basis. Nepheline syenite, where it is available at favourable prices, is used in preference to sodium feldspar in high volume ceramics such as sanitaryware, earthenware, and stoneware. Potassium feldspar commands the highest price and is used mainly in high voltage electrical porcelain, where its higher price can be justified by its technical advantages over sodium feldspar and nepheline syenite for this application.

Developments in ceramics manufacturing technologies have grown rapidly in recent years and will have an increasing influence on the market for flux materials. These developments include the following:

- fast firing and once-firing of ceramics
- the use of prepared bodies and manufactured fluxes and glazes
- dry pressing of tableware and tile and pressure casting of sanitary ware

Anorthosites have generally not been recognized as attractive fluxes for ceramics manufacture. They have relatively high fusion points (1500°C) compared to the lower melting soda-and potash-bearing feldspars and nepheline syenites. Nevertheless, some promising research has been conducted on the use of anorthosites in tile manufacture. These researches have focussed on two aspects of anorthosites: fluxing properties and physical properties during firing.

Lyng and Gamlem (1974) found that anorthosites were effective fluxes when fired under relatively short cycle times. The use of anorthosites resulted in dense and strong products for use in electrical porcelain and

vitreous china. The results were attributed to the fact that the plagioclase feldspar in anorthosites exists in both low- and high-temperature forms which are reactive when subjected to fast firing cycles of 1 to 2 hours. The low temperature form presumably fuses to cause sintering while the high-temperature form remains substantially unaltered, thereby generating high density and mechanically strong products. With long firing cycles of a day or so, the low temperature form presumably reacts with other material rather than fusing and generates a higher melting form instead, thereby eliminating its low-temperature fluxing capability. This finding may have applicability in the production of electrical porcelains and vitreous china as well as wall tiles.

Gamlem and Lyng (1974) also investigated the production of floor and wall tiles using anorthosite. The principle behind these experiments was that anorthosite could be used as a cheap substitute for wollastonite in tile bodies, yielding a body with good fast firing properties and low moisture expansion. The results indicated that ceramic bodies based on the anorthosite-ball clay system could not be used for the production of wall tiles. However, ceramic bodies based on the anorthosite-ball clay-nepheline syenite system may have potential for floor tile production. Moreover, ceramic bodies based on the anorthosite-ball clay-talc system (40 weight % anorthosite, 30 weight % ball clay, 30 weight % talc) had good fast firing properties at temperatures below 1200°C, favourable water absorption and shrinkage properties for wall tiles. The products showed good moisture expansion properties and favourable mechanical properties.

Anorthosites have other potential applications which do not depend on fluxing capability for their appeal. Research conducted in the early 1970s has indicated that high anorthite composition has a positive effect on the properties of ceramics. Radowka (1974) found that anorthite formed as an intermediate phase in vitreous tableware in the presence of CaO. The anorthite contributed to an increase in the content of secondary mullite and hence the fracture toughness of the ceramic. Baudran and Ducarre (1974) found that by replacing clay with a synthetic calcium mineral containing a high percentage of anorthite resulted in products having uniform thermal expansion over the firing range, a wide firing range, and reduced shrinkage under fast/once-firing conditions. Both porous and non-porous bodies could be prepared. These results indicate that ceramic bodies incorporating anorthosite could have useful properties. The results apparently indicate that anorthosites with a high anorthite content; e.g., labradorite and bytownite, would be preferable to anorthosites having a low anorthite content.

British patent 1,535,515 describes an invention in which anorthosites were advantageously utilized in the production of wall tiles. When heated to about 1000°C they permanently expand by about 1%, thereby compensating for shrinkage of clay-containing material in the tile mixture and thus minimizing shrinkage of the tiles during firing. A Soviet patent (SU 1,296,546) describes the use of anorthosite in a tile body containing a nepheline-aegerine-eudialyte-feldspar waste, clay, bentonite, and broken tile. The tile body was fired for 17 minutes at 980°C, glazed, and again fired for 28 minutes at 950°C. The resulting tile product was reported to have increased strength and reduced swelling due to moisture compared to a similar tile not containing anorthosite.

Another Soviet patent (SU 1,289,861) describes the use of an anorthosite and aegerine mixture to produce a high heat (up to 1300°C) and wear-resistant coating for chamotte articles, and decorative and anti-corrosion coatings for building materials. The anorthosite contributes SiO_2 and Al_2O_3 to the product, which are said to improve the properties of the material.

Fillers and Extenders

As functional fillers, nepheline syenites are used in paints and coatings to improve opacity, film strength, and chalk resistance as well as to reduce costs. In plastics, syenite fillers are used to improve a number of physical properties of the base resin and to reduce costs. The fillers add strength to rubbers, adhesives, and sealants. The properties of the fillers contributing to their increased use in the noted applications include high dry brightness, good dispersion, inertness, pH stability, hardness, resistivity to acids and low oil absorption.

Paints

Nepheline syenite fillers can be used in both interior and exterior formulations and in both solvent and water-based coatings. They are used in highly pigmented and translucent stains and clear films. Applications range from relatively inexpensive traffic paints to fine furniture finishes and tannin stabilisers. The hardness of nepheline syenite contributes to film toughness and hence scrubbability, and it competes with ground silica and feldspar with these attributes in filler markets.

The low tint strength of nepheline syenite means that it does not provide the colour undertones sometimes associated with other mineral fillers and extenders. Thus smaller quantities of expensive colouring agents are required when using syenite fillers.

Nepheline syenites are expected to see increased use in paints and coatings. There is a significant trend to the use of tougher coatings, especially for industrial paints. These coatings are being applied more thinly and require syenite fillers to increase the toughness of the film. There is also a trend to use single or two part paint systems in place of three part systems employing a primer, undercoat and topcoat. Again, heavy duty paint systems using syenite fillers are able to perform better than the old three part paint systems. Finally, there is a strong trend away from the use of solvent-based paint systems to water-based and high solids systems such as powder coating. Syenite fillers perform extremely well in these situations, especially for powder coatings where heat resistant, chemically resistant and easily dispersed pigments are required. Fillers and extenders with a high vehicle demand and chemically bound water such as kaolin are not suitable for these coatings, whereas syenite fillers and extenders meet the requirements.

Plastics

Nepheline syenite has applications as a filler and extender in plastics. Because it is silicate-based, it performs in a similar manner to the various silicas when used in fine particle sizes. Typical applications for syenite fillers include polyester microwave ware and large animal feeders, high traffic vinyl flooring, PVC cove base moulding, polyacrylate corrugated roofing, and polyester signs and building facades.

The physical properties that make nepheline syenite attractive as a filler and extender in paints and coatings apply to the plastics industry as well. These properties include low vehicle demand and low viscosity at high pigment loadings, high dry brightness and low tint strength, resistance to stains, abrasion, and chemical attack, and good dispersion characteristics. The index of refraction is also a particularly important property. Nepheline syenite has a refraction index of 1.53, which is close to that of the most commonly used vinyl resins. When combined with the low optical dispersion of syenite fillers, the material is virtually invisible in the clear resin. Thus smaller quantities of expensive colouring agents are required in comparison to, for example, calcium carbonate fillers.

The largest application in plastics for micronized nepheline syenite is as a filler in various PVC plastics and in epoxies and polyesters. The syenite provides excellent impact strength, dimensional stability and high heat deflection temperatures with high loadings in injection moulding thermosetting polyesters. They can be used at high loadings in castable epoxies and polyesters when combined with suitable coupling agents.

Rubber, Adhesives and Sealants

Nepheline syenite specialty fillers find use in silicone rubber auto parts, neoprene rubber gaskets, styrene butadiene rubber (SBR) building products, and polyvinylacetate (PVA) adhesives. The properties of the materials contributing to their use in these applications include high dry brightness, ease of dispersion, resistance to chemical attack, stain and abrasion resistance, and refractive index.

The low optical dispersion and refractive index of nepheline syenite is important to the adhesives industry. The properties of the syenites permit the manufacture of adhesives that dry clear on wood products and are relatively translucent on glassy products.

In silicone rubber applications, nepheline syenite provides properties identical to pyrogenic or ground silica in silicone rubbers, but without the added cost of the silica. Moreover, silicone rubber products formulated with nepheline syenite are much whiter than the comparable silica-formulated products. This is a definite advantage in the market.

Many of the same comments regarding the potential of nepheline syenite in paint, plastics and rubber applications could be said of anorthosite. Provided very low-iron, white anorthosite was available, there would appear to be no reason why finely-ground anorthosite could not be used as a filler in many applications. If material similar to the very fine residue resulting from the Kemira alum production process was available, there should be significant market potential.

Other Uses

Other uses suggested in the 1940s and 1950s for nepheline syenite included refractory cements (intermediate temperatures) and in the production of ultramarine, lac substitutes and "laundry blue." Each of these proposed uses has been superseded by more modern materials or changes in process technology (Allen and Charsley 1968).

An interesting new use is for feldspar as a fluxing agent for enhanced combustion of flue gases derived from the delacquering of aluminum beverage cans. Aluminum cans are coated with lacquer which must be removed prior to recycling. It has been found (Sjoberg and Gullman 1987) that injection of feldspar particles or a 50/50 mixture of feldspar and lime is useful in agglomerating the dust particles and in removing the toxic compounds. The process is very similar to the electrostatic precipitation process used to remove flue dusts from thermal power plants and cement kilns.

Mineral Wool

In Canada, high-iron nepheline syenite is used as a

Table 5
Typical Composition for Mineral Wool

	Weight %
SiO_2	24-32
Al_2O_3	8-12
Fe_2O_3	2-3
CaO	16-21
MgO	10-13
LOI	26-29

low-cost flux and source of alumina and silica in the production of mineral wool. The other principal ingredient in mineral wool production is blast furnace slag, although other materials such as argillaceous dolostones, calcareous shales, basalt and other metallurgical slags can be used. A typical composition for mineral wool is shown in Table 5.

A very high calcium anorthosite would provide a good starting point for mineral wool manufacture if the material was competitive in cost to blast furnace slag. The CaO-Al_2O_3-SiO_2 eutectic has a melting point of 1165°C at a mix of 23.3% CaO, 14.7% Al_2O_3, and 62.0% SiO_2. Even if an anorthosite source does not meet the desired chemical composition, it could be used in more limited quantities as a substitute for nepheline syenite, slag, or basalt if the delivered price is competitive.

The use of anorthosites in the manufacture of more refractory fibres is also possible. These fibres require a higher silica, alumina, and calcium content than does mineral wool. The starting point is generally a high alumina material such as bauxite, mullite, or kyanite. Incorporation of small amounts of anorthosites may be possible in most blends.

Abrasives

Anorthosites and syenites can be used in abrasives and scouring soaps because of their angular fracture and medium hardness. The two-dimensional cleavage pattern of the mineral causes feldspar to form sharp-edged, gritty particles. A/S Gabbrolit in Norway produces anorthosite scouring powders. Ontario sources should prove to be equally good in these applications, especially if the material has high brightness. The market, however, for anorthosite abrasives is decreasing as powders are being displaced by liquid cleansers containing very finely ground silica. One growing market for low-grade feldspathic sand is for use in sand blasting, displacing silica sand and eliminating concerns with free silica. Anorthosites and syenites would compete against garnet and olivine in this application.

Nepheline syenite has been used as a bonding material in the manufacture of grinding wheels. The syenite fuses with the corundum grains during processing to form a strongly bonded ceramic. The translucency of the syenite allows the desirable blue colour of the corundum to show, while the good thermal shock resistance of nepheline syenite helps to prevent cracking of the wheel due to thermal shock (Allen and Charsley 1968).

Welding Fluxes

Feldspathic materials are used in small amounts in the production of welding electrodes. The materials are used to aid in the extrusion and binding of the coating fluxes; slag formers in the flux; and as the prime source of alkali ions in the arc plasma. The alkali silicate content of welding electrode coatings can be up to 12% of the total dry blend mix. Welding fluxes should be consistent in particle size and not exceed 250 µm in order to avoid unpredictable welding characteristics. The standard particle size is typically in the 70 µm range.

Feldspar is incorporated into the dry blend for coating the electrodes. In general, potassium-bearing feldspars are more popular as they produce a smoother arc. Nepheline syenite possesses the appropriate chemistry for use as a welding flux and should be able to be used in this application as a direct substitute for feldspar and synthetic alkali silicates.

Anorthosites do not appear to have much promise in welding flux applications. The calcium content mitigates against the development of a smooth arc, especially at low voltages due to the higher dielectric constant. Ca-feldspars are also higher melting than Na- or K-feldspars, meaning a higher current density must be applied. This raises the electrical energy requirement and the requirement for more expensive, heavy duty welding equipment.

Processes for Chemical Products

Acid and alkaline (sinter) processes are employed in four plants currently in operation. An acid leach process is used for anorthosite in Finland for the production of aluminum sulphate and other chemical products. Alumina from nepheline syenite is produced by lime sinter techniques at three plants in the U.S.S.R.; the raw material is derived from two distinct deposits. In addition, considerable research, from laboratory to mini-plant scale, has been devoted for many decades to the feasibility of alumina extraction from anorthosites and nepheline syenites as an alternative to the Bayer process and to the dependence on bauxitic ores.

Acid Processes

Lapinlahti Anorthosite, Finland

Anorthosites and nepheline syenites can be sources of various inorganic chemicals such as aluminum sulphate (alum). The Soviet Union and Finland have been the main researchers into these applications. Kemira Oy, a large Finnish mining and chemicals company, has conducted extensive investigations on the processing of anorthosites and is reported to produce 65,000 to 100,000 tonnes per year of aluminum sulphate from anorthosite. The company operates an anorthosite quarry at Lapinlahti in northern Finland. The material is processed at a plant at Harjavalta.

There are several problems associated with the production of chemicals from anorthosites. If a sulphuric acid extraction method is used, a significant problem is the formation of silicic acid, which has a strong tendency to gel. This makes filtration of the undissolved product difficult. In addition, there is a significant production of undissolved by-product silica and calcium sulphate. If hydrochloric acid is used similar problems result. Finally, anorthosites vary greatly in their leaching behaviour with mineral acids, and processes which work with one type of anorthosite may not work with another type. Work conducted by Kemira Oy on Finnish anorthosites highlights some of the problems mentioned.

Finnish patent application 771014 discusses the leaching of anorthosite with a mixture of sulphuric and hydrochloric acid at 100°C for 1 to 2 hours. The alumina content in the filtrate was only about 6%, making the process uneconomic. The undissolved silica residue and precipitated calcium sulphate were calcined to produce anhydrous calcium sulphate, cement, and synthetic wollastonite. In the subsequent Finnish patent application, number 800329, it was disclosed that the use of very coarse grained anorthosite would avoid the problem of silicic acid gel formation when using mineral acids. Using 6N HCl at 100°C a yield of approximately 36% of the contained alumina was obtained. The filtered and washed solution residue was claimed to be suitable for mixing with cement to form a lightweight, porous material having good thermal insulation characteristics.

Finnish patent 71916 describes a process for the production of aluminum sulphate from anorthosite yielding a high quality alum and a very finely divided and white residue having use in the manufacture of cement, as a filler, and as a replacement for satin white in paint and paper manufacture. In the process finely crushed (50% less than 40 µm and up to 60 µm) anorthosite is treated with 93% sulphuric acid. (The anorthosites used differed markedly in their reactivity, the more reactive material having a higher alumina and silica content and lower iron content than the less reactive material.) The acid is diluted with water to approximately 50%. The dilution provides the heat for the reaction, which must be kept in the range of 100°C to 130°C. The insoluble residue is separated from the filtrate, washed, and selectively filtered to yield a finely divided white silica residue (specific surface area of 50 to 70 m^2/g) and an anhydrous calcium sulphate. The aluminum containing filtrate is diluted with water to a concentration of 10 to 11% alumina. Alum is recovered by the addition of 93% H_2SO_4 and aluminum hydrate to precipitate the aluminum sulphate, which has an alumina content of approximately 17%. The aluminum hydroxide contributes approximately 50% of the total alumina in the final product.

The silica-containing residue was found to be non-pozzolanic but to be an excellent binder in white cement when used in proportions up to 50%. The material had high brightness, 81% to 82.4%, permitting its use as a filler in white cement and as a replacement for satin white in paper manufacture. A similar process route based on nepheline syenite has also been proposed (Allen and Charsley 1968).

Synthesis of Zeolites

Zeolites are crystalline hydrated alumino silicates containing positively-charged metallic ions (cations), in most cases Ca, Na, or K, in cavities within them. This feature is also embodied in the structures of the feldspar and feldspathoid minerals. Zeolites are remarkable for their continuous and in part reversible

dehydration and their property of readily exchanging constituent cations with other cations. Furthermore, these structures are effective molecular sieves.

The mineral composition of anorthosites and nepheline syenites makes them theoretically attractive starting materials for the production of synthetic zeolites. The crystal structure must be disrupted to allow penetration of the exchangeable ions. This is most easily accomplished by rendering the feldspar/feldspathoid minerals amorphous by means of melting or by treating the material with strong caustic or acid solutions.

Nepheline syenite reacts favourably to treatment by sulphuric acid or caustic soda to form intermediates which can be zeolitized. Feldspathoids such as nepheline are particularly amenable to acid treatment due to the more open structure, relative to feldspar structures, and high Al:Si ratio in the framework. The alumina is removed in solution and the lattice collapses to form a gelatinous silica. Gelatinization with acid distinguishes feldspathoids from feldspars. The process of zeolitization is essentially an accelerated version of the natural degradation process. The silica gel can be transformed into a colloidal suspension and rendered amorphous, disrupting the Si-O and Al-O bonds and allowing access into the crystal lattice by exchange cations. Caustic treatment of nepheline syenite follows a slightly different process, wherein the crystal structure is transferred by a process of gelatinization and reversible hydration.

It has been shown in laboratory investigations that a wide range of zeolites could be synthesized readily from alumino silicate gels. The product depends on the gel composition, the nature of the reagents and the conditions of crystallization. Although the gel components and composition direct the structure of the final product, all zeolites are amenable to post-synthesis modification; the non-framework cations can be replaced through ion exchange, and the framework composition itself can be altered (Newsam 1986).

The synthesis of zeolites based on nepheline syenites and anorthosites has not advanced beyond laboratory investigations to date. In the case of anorthosites, it was also noted by the United States Bureau of Mines (Barclay 1984) that when limestone and anorthosite are mixed in a 2:1 ratio (weight basis), sintered, and then leached with 10% Na_2C0_3, a calcium-sodium zeolite is formed in the ungelled leach residue.

Acid Extraction of Alumina

Acid processes for the extraction of alumina from non-bauxite resources have received considerable attention as a potentially less expensive solution than the schemes for alkaline processing of aluminous materials, which are energy- and capital-intensive. Anorthosites as alumina sources were investigated in many countries because of its high Al_2O_3 content. By definition, anorthosite contains between 18.9% Al_2O_3 (90% oligoclase composition) and 36.7% Al_2O_3 (100% anorthite composition). Major difficulties in the acid processing of anorthosites include the following points:

- The dissolution rate of Al_2O_3 in acid is generally slow. Remedies have included prior melt-quench treatment, the use of fluorides as a catalyst or the selection of suitable mineralogical composition.
- Acid demand is high; an inexpensive supply of acid or acid regeneration is essential (Deustschman 1982).

Mineralogical Composition

It had been shown by 1920 in Norway that there existed very large variations in the extractability of alumina from different anorthosite deposits. This difference was attributed to variations in the plagioclase composition. It was concluded from this and later work that anorthosites containing 50% or less anorthite are not suitable for direct acid treatment, while alumina is easily extracted when using anorthosites with 60% or more anorthite content.

Gjelsvik (1980) states that leachability is a function of the Si:Al ratio, which must be below about 1.5:1 to prevent the dissolution of Al ions being masked by an insoluble silicate structure. The condition that appears to be necessary for acceptable dissolution is collapse of the silicate structure as Al ions are leached from it.

The dissolution process follows a shrinking core model. The explanation for the leaching process is described in more detail below.

- Anorthosite with a Si:Al ratio of 1:1 is attacked by acid such that H^+ ions break the Ca-O and Al-O bondings. Aluminum and calcium are replaced by H^+, which becomes attached to the oxygen to form Si-OH groups.
- The $Si(OH)_4$ liberated in the reaction is unstable in hot acid and polymerizes and precipitates as silica gel.
- In contrast, in anorthosites with a high Si:Al ratio, each aluminum ion is surrounded by many silicon ions. Even when the aluminum ions at the surface are leached away by acid, the remaining Al ions are so deeply buried in the structure and shielded by silicon-oxygen groups that the H^+ ions cannot interact with them.

- The limiting Si:Al ratio is approximately 1.5:1. At this limit or below there are sufficient Al ions that when they are leached from the surface a structure is formed which is porous enough so H^+ ions can diffuse through into the unattacked mineral solution. Importantly, when the Al ions are removed, the surrounding Si ions are not liberated from the structure and therefore the anorthosite crystal structure is preserved. The resulting residue looks and behaves like sand, permitting easy disposal.

The factors just noted are the basis for the HCl-based Anortal Process described later in this paper.

Melt-Quench Technique

Experiments conducted by the U.S. Bureau of Mines found that when anorthosite was melted and quenched alumina recoveries greater than 95% were possible using relatively short leach times with 16% sulphuric acid.

Work at CANMET (Hamer 1976) examined the melt/quench process using a variety of mineral acids and anorthosite (labradorite-type) from the Lac St. Jean region of Quebec. The chemical analysis of the anorthosite (Table 6) was similar to that of several Ontario deposits.

The melt/quench process is highly energy intensive. The crude anorthosite must be ground to -65 mesh before melting. Melting takes place in an electric furnace at a temperature in the 1500° to 1540°C range, but the melt must be heated to 1600° to 1650°C before pouring into quench moulds. The amorphous melt is then crushed to -65 mesh and reflux leached with acid. Yields of alumina using various acids were reported to be:

- 95% recovery with 15% H_2SO_4 using 125% of the theoretical amount of acid to form sulphates.
- 95% recovery with greater than 10% HCl using 105% of the theoretical amount of acid to form chlorides.
- 92.4% recovery with 30% HNO_3 using 100% of the theoretical amount of acid to form nitrates.

Due to the energy cost penalty and high reagent consumption, this is not a favoured process route by researchers, although the technique could be effective for rocks of oligoclase to labradorite composition.

Fluoride-Assisted Acid Leach

The use of the aggressive fluoride ion in conjunction with a mineral acid has been demonstrated to disrupt the silicate structure of the alumino silicate minerals in anorthosites to allow effective leaching and extraction of alumina content.

Table 6
Anorthosite Composition from Lac St. Jean, Quebec

	Weight %
Al_2O_3	27.49%
SiO_2	53.81%
Fe_2O_3	2.31%
CaO	10.56%
Na_2O	4.97%
K_2O	0.53%

Excellent bench-scale results were obtained by the U.S. Bureau of Mines in the extraction of alumina from Wyoming anorthosite using hydrochloric acid (HCl) and fluoride (F) (Bremner 1982). Using 95% of the stochiometric HCl requirement and an F/Al mole ratio of 0.27, 90% of the alumina was extracted by countercurrent leaching. Three fluoride sources, i.e., CaF_2, Na_2SiF_6, and H_2SiF_6 were used and gave similar yields. CANMET obtained similar results with HCl-H_2SiF_6, leaching of anorthosites from Lac St. Jean in Quebec.

A variation of the HCl-F anorthosite leach technique is the HCl-F-gas sparging crystallization process developed by USBM and described later on in this review.

The later examination of other Canadian anorthosite deposits, including Shawmere anorthosite in Ontario, found that material from some of them was amenable to extraction without the assistance of fluoride. Yields of 85% to 90% alumina were obtained from fresh unaltered rock samples with the mineralogical composition of bytownite for the plagioclase feldspar content. Alcan Aluminum Ltd. developed a variant of the HCl-gas sparging process without the assistance of fluoride, using a high-calcium anorthosite; this process is outlined later in this section.

Anortal HCl Leach Process

The process was operated for more than four years at the pilot-plant scale in Norway with the objective of exploiting that country's significant anorthosite resources. I/S Anortal was a joint venture formed in 1976 by Norwegian aluminum producers Elkem and ASV. The process is described by Kvande (1987) as follows:

"The leaching of crushed anorthosite (-3 ± 0.3 mm) may be done by hydrochloric acid followed by sparging with HCl gas. Calcium ions are precipitated with excess HCl, and the calcium chloride hexahydrate

(CCH) is reacted with the residue for return of the HCl to the leaching stage in the process. Crystallization of aluminum chloride hexahydrate (ACH) occurs in two stages by addition of HCl gas. To reduce the impurity level, the first stage is carried out at about 70°C, after which the product is recovered. The impure crystals from the second stage (at about 40°C) are redissolved again in the process solution prior to the first stage."

"The calcination is also performed in two stages. First, the decomposition is carried out almost completely at 450° to 500°C, according to the reaction:

$2AlCl_3 \cdot 6H_2O = Al_2O_3 + 6HCl + 9H_2O$"

"Indirect heating is used to recover the hydrogen chloride. The decomposition product is heated to 800°C by direct heating to obtain an alumina from which sodium chloride can be removed by washing. The final calcination is then carried out at 1000° to 1100°C in order to remove residual chloride and water. Figure 3 illustrates the Anortal process for production of alumina from anorthosite."

"The alumina produced by the Anortal process is basically different from the Bayer alumina, since it is formed by dehydration of calcination of $AlCl_3.6H_2O$, rather than by dehydration of $Al(OH)_3$. The calcination step required about 25% more energy than for the Bayer process. Furthermore, economic considerations have shown that the capital costs of the Anortal process may be somewhat higher and the operating costs are slightly higher, but the working capital is lower."

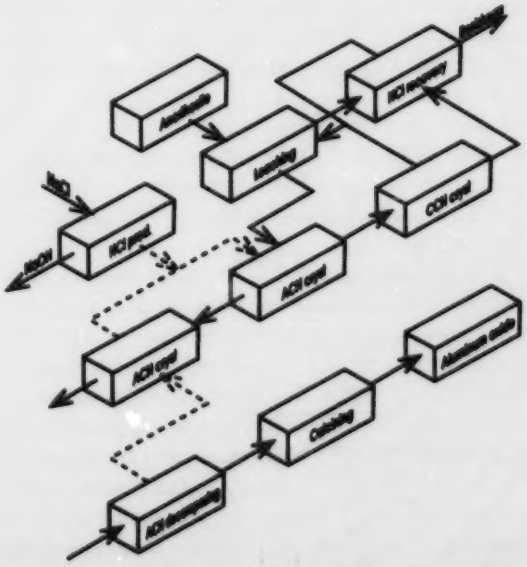

Figure 3. Anortal Acid Process for the Production of Alumina from Anorthosite. (from Kvande 1987).

United States Bureau of Mines Hydrochloric Acid – Fluoride – Gas Sparging Crystallization Process

The U.S. Bureau of Mines has designed a fluoride-assisted hydrochloric acid (HCl) leaching process for finely-ground anorthosite from Wyoming; the process included the crystallization of $AlCl_3.6H_2O$ (ACH) from the pregnant liquor by HCl gas injection. Approximately 90% of the alumina values were recovered from the anorthosite when a ratio of 0.14 mole of fluorine per mole of aluminum was used.

Figure 4 is a simplified flow sheet of the process. Eisele and Bauer (1983) describe it as follows:

"Aluminum is dissolved in the HCl-F leaching liquor and forms $AlCl_3$. Many of the other constituents of anorthosite also dissolve and form metal chlorides. Aluminum is crystallized from the solution and, at the same time, separated from most of the other chloride salts by sparging HCl gas into the liquor. Sodium chloride co-crystallizes with $AlCl_3.6H_2O$ and is separated after calcining at 550°C. The $AlCl_3.6H_2O$ is converted to water-soluble Al_2O_3, while NaCl does not decompose and is removed by washing with water. Since large quantities of Ca, Na and Fe are dissolved in leaching, a large bleedstream must be taken, or the liquor will become saturated with chloride salts. The remaining mother liquor is recycled. The bleedstream and the NaCl solution from alumina washing are combined and evaporated to recover free HCl and to crystallize the chloride salts. The salts are decomposed by calcining at 800°C, and more HCl is recovered. An acid-adjustment step combines the HCl recovered from the different sources and returns the proper quantities to leaching and sparging."

The alumina produced was reported (Eisele and Bauer 1983) to be purer than Bayer alumina except for MgO and SiO_2 content. It is noted that the thermal decomposition steps to recover Al_2O_3 from $AlCl_3.6H_2O$ and to recover HCl from waste chloride salts will be energy-intensive. A problem with the technique is that about 40% of the fluoride leaves with the leached residue; some of this is recoverable with processing of the residues to recover their chloride values.

ALCAN Hydrochloric Acid – Gas Sparging Process

Alcan Aluminum Ltd. developed a process in the late 1970s that could produce a cell-grade alumina from high-calcium anorthosites; a typical rock analysis suitable for this process is provided (Table 7; Deutschman 1982).

The Alcan process relies upon the digestion of

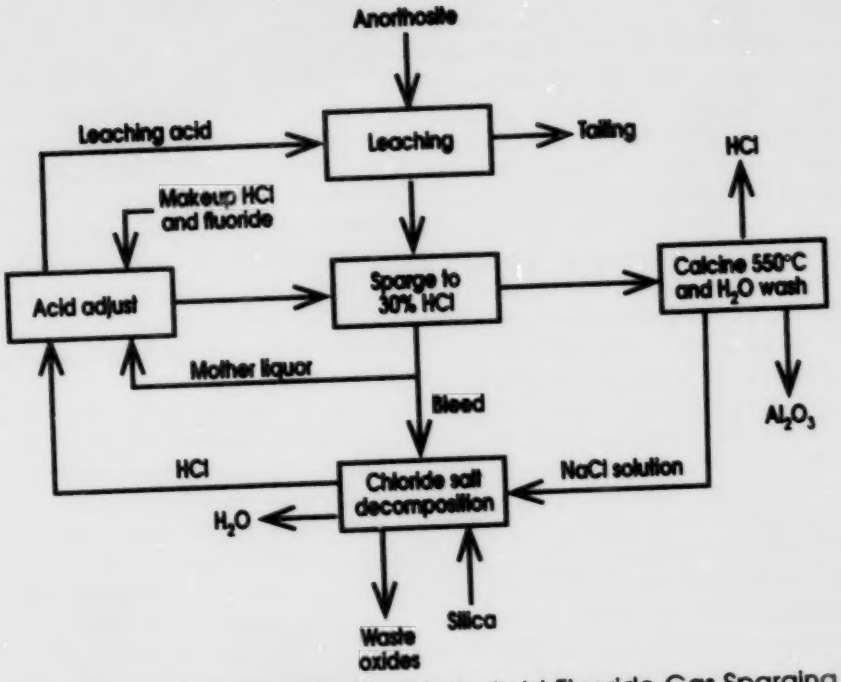

Figure 4. Simplified Flow Chart of the Hydrochloric Acid-Fluoride-Gas Sparging Crystallization Process (from Eisele and Bauer 1983).

ground (less than 100 mesh) anorthosite in a concentrated liquor of HCl and $CaCl_2$ at a temperature of 170°C and a pressure of 9 to 10 kg/cm^2. More than 90% of the contained alumina can be dissolved within 15 minutes under these conditions. The alumina is precipitated from the pregnant solution as a crude aluminum chloride hexahydrate, $AlCl_3.6H_2O$ (ACH) by HCl gas sparging. The ACH crystals are filtered and washed with concentrated HCl and then recrystallized from water to separate out the NaCl crystals by means of fractional crystallization. The ACH is then washed and thermally decomposed to yield cell grade alumina with the following analysis (Table 8).

Table 7
Analysis of Rock Suitable for the Gas Sparging Process

	Weight %
Al_2O_3	29.8%
SiO_2	46.5%
Fe_2O_3	2.3%
CaO	15.3%
Na_2O	2.3%
MgO	0.8%
TiO_2	0.1%
K_2O	0.1%

The overall yield of the process is 70 to 80%. The process is illustrated in Figure 5. The Alcan process offers a number of advantages over other process schemes based on acid processing of anorthosites. These include:

- Relatively fast dissolution of Al_2O_3
- A reduction in the demand for acid and/or an easy scheme for acid regeneration
- Relatively easy separation of the Al_2O_3 from the Ca and Na salts.

The high concentration of $CaCl_2$ provides a built-in azeotrope-breaker for the degassing of the liquor bleed. It also assists in the precipitation of ACH. The digestion of anorthosite is relatively rapid and attains a relatively high yield. The MgO and P_2O_5 impurities are removed by a combination of primary precipitation from $CaCl_2$ brine, recrystallization, and recycling part of the ACH from the secondary to the primary sparging stage. The NaCl leaves the process as an easily disposable or re-usable solid rather than as a brine. Finally, the high concentration of $CaCl_2$ in the primary liquor appears to have little bearing on the CaO impurity.

The regeneration of acid is one of the keys to the economics of the Alcan process. There are two possible routes to regenerate HCl, given the large quantities of $CaCl_2$ formed in the reaction. These routes are:

1. $CaCl_2 + SiO_2 + H_2O \longrightarrow 2HCl + CaSi0_3$
2. $CaCl_2 + H_2S0_4 \longrightarrow 2HCl + CaS0_4$

The first reaction can use the anorthosite residue as the source of silica. The amorphous nature of the residue, relatively high reactivity and high surface area allow for efficient acid regeneration and elimination of a major waste disposal problem. The by-product calcium silicate could be used in the manufacture of cement or refractory calcium silicate

Table 8
Analysis of Cell Grade Alumina

	Weight %
Al_2O_3	99.966%
Fe_2O_3	0.002%
SiO_2	0.008%
MgO	0.005%
P_2O_5	0.0002%
CaO	0.009%
Na_2O	0.010%
TiO_2	0.0004%

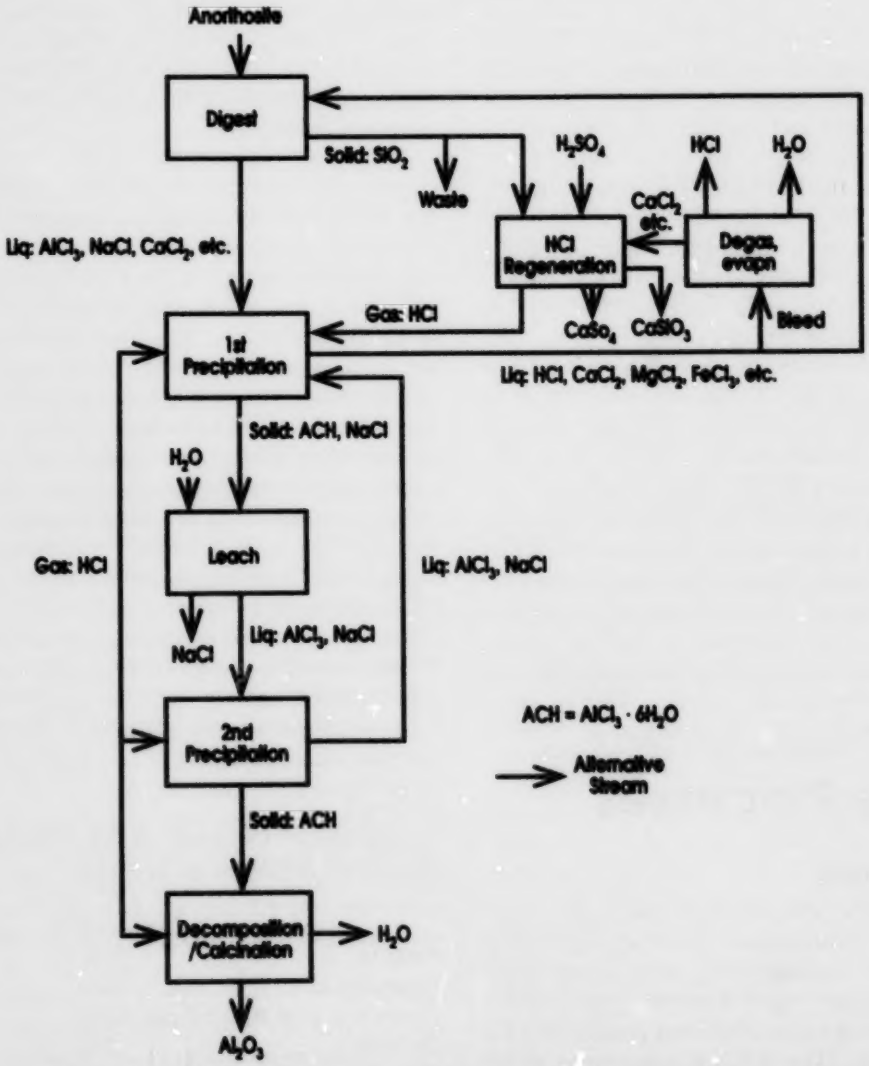

Figure 5. Proposed Acid Process (Alcan) for Production of Alumina from Anorthosite (from Deutschman 1982).

products. The second reaction can be used in a location where a cheap source of sulphuric acid is available. It can be used either with precipitated $CaCl_2$ or with $CaCl_2$ solution. The by-product gypsum could be used in the manufacture of gypsum wallboard or other gypsum products.

Organic Acid Extraction of Alumina

Bioleaching of Feldspathoid Minerals

Feldspathoid minerals such as nepheline ($(Na,K)AlSiO_4$) and leucite ($KAlSi_2O_6$) degrade readily and can be leached in mineral acid and also in organic acids.

Organic acid leaching of nepheline has been studied under batch and semi-continuous laboratory conditions for the extraction of alumina. King and Dudeney (1987) report on the bioleaching of nepheline syenite from the Bancroft area. The material was finely crushed, screened and leached using Aspergillus Niger for the production of citric and oxalic acids. The fermentation and leaching were carried out on a semi-continuous basis and the aluminum recovered by resin ion exchange as aluminum citrate at a pH of 3.1 or greater. The recovery of aluminum was approximately 25% of the theoretical maximum loading. The sodium and potassium citrates produced in the process can be recovered by crystallization. The fungi used in the process absorb approximately 6% of its mass of silica during growth. The fungi and silica can be recovered by pH adjustment or the use of a flocculant and potentially used as a soil conditioner. No estimate of the economics of the process was provided.

Potassium and aluminium can also be recovered by a bioleaching process (Rossi 1978). Leucite was used as the starting material. The results were discouraging in terms of the yields of potassium and aluminium. However, the work does illustrate that potentially low cost, environmentally attractive routes to alumina, potassium, and other metals and chemicals may be possible.

Alkaline Processes

Sinter Processes

Sinter processes generally have very high energy requirements for the extraction of alumina from nepheline-bearing ores and anorthosites. Large quantities of limestone are required and the large volumes of by-products need to be converted into cement for economic viability. The U.S.S.R. operations which utilize nepheline syenite or nepheline concentrates from two separate areas are examples of multiple product utilization. Alumina production from the Kola Peninsula deposit can in fact be considered as a by-product of phosphate production from that source.

Laboratory investigations during the 1970s in the U.S.A. and Canada confirmed the technical feasibility of the extraction of alumina from anorthosites by lime sinter-caustic leach and lime-soda sinter-caustic leach processes.

Nepheline Syenite-Lime Sinter Process

Khibiny Mountain Nepheline Syenite, U.S.S.R.

Large-scale mining of apatite takes place at Khibiny Mountain in the Kola peninsula. The ore body is a lens shaped apatite-nepheline deposit overlain by nepheline syenites. The ore body is in two distinct zones; the upper zone having a mean P_2O_5 content of 26 to 28% and the lower zone a P_2O_5 content of 16 to 18%. The mineralogical composition of the zones is shown in Table 9.

Mining is conducted underground due to the severe climate and the ore is transported to Kirovsk for crushing and separation. Apatite is removed by flotation for subsequent production of phosphate fertilizer and the titanomagnetite is separated from the nepheline tailings for use in iron-making and recovery of titanium. The nepheline concentrates contain 90% to 93% nepheline and have an approximate composition of 30% alumina, 20% soda and potash, 43% silica and 3% to 4% ferric oxide (Allen and Charsley 1968).

The nepheline concentrates are shipped to two alumina plants near Leningrad for processing into alumina, cement, and sodium and potassium carbonates. The first plant at Volkhov was started in 1951. A second plant at Pikalevo, near Volkhov, was started up in 1959. The lime sinter-caustic leach process (known as the VAMI process) results in the production of large quantities of by-product cement material and sodium and potassium carbonates. These by-products have a ready market in the Soviet Union and con-

Table 9
Composition of Zones in the Khibiny Mountain Nepheline Syenite

	Upper Zone	Lower Zone
Apatite	65%	45%
Nepheline	20%	30%
Pyroxene and Amphibole	10%	18%
Sphene	2%	3%
Titanomagnetic	2%	3%
Other Minerals	1%	1%

Table 10
Alumina Analyses from Two Sources

	(Minnes et al. 1983)	(Allen & Charsley 1968)
Al_2O_3	99.39%	99.20%
Fe_2O_3	0.001%	0.31%
Na_2O	0.37%	0.37%
SiO_2	0.062%	0.12%
L.O.I.	0.22%	n.a.

tribute to the economics of the process.

The VAMI process is illustrated in Figure 6. The dried nepheline concentrate is ground to about 50% -170 mesh and pulped with limestone to form a sludge. The sludge is reground in the wet state to a fineness of over 95% -170 mesh. The pulp is passed through a rotary sinter kiln where a sinter of dicalcium silicate and aluminates of sodium and potassium is formed at approximately 1300°C.

The reaction is stated as:

$$4CaCO_3 + (Na,K)_20{\cdot}Al_2O_3{\cdot}2SiO_2 \longrightarrow (Na,K)_20{\cdot}Al_2O_3 + 4Ca_2SiO_4 + 4CO_2$$

The sinter is cooled and then crushed in a cone crusher and wet ground in a ball mill to 3% +10 mesh; 30% -200 mesh, with the balance within the size range -10, +40 or +50 mesh. The pulp is leached in a tube digestor with caustic soda and recovered mother liquor. The leach passes continously to a vacuum filter condenser to remove the alkali aluminates. The dicalcium silicate slurry, called nepheline slurry, is washed and thickened for subsequent use in the manufacture of Portland cement.

Desilication of the aluminate solution is accomplished in pressurized autoclaves using a silver catalyst and the solution is filtered. The reaction sequence is:

$$6NaAl_2O_3 + 5Na_2SiO_3 + Ag \longrightarrow (3\text{-}4)Na_20{\cdot}3Al_2O_3{\cdot}5SiO_2{\cdot}nH_2O + (8\text{-}10)NaOH + Ag$$

The potassium reaction is similar. The filtrate from the desilication circuit is returned to the primary nepheline-limestone wet grinding circuit. The solutions are passed to carbonization towers where the alkalis remain as soluble carbonates and the alumina is precipitated as aluminum hydroxide. The hydroxide is calcined to form alumina and the carbonates are separated by selective crystallization. The reaction sequence is:

$$2(Na_2K)AlO_2 + CO_2 + 3H_2O \longrightarrow 2Al(OH)_3 + (Na,K)_2CO_3$$

$$2Al(OH)_3 + \text{heat} \longrightarrow Al_2O_3 + 3H_2O$$

The alumina is reported to be similar in quality to alumina derived from bauxite. Reported analyses from two sources are shown in Table 10. The sodium and potassium carbonates are reported to have the analysis shown in Table 11.

Table 11
Sodium and Potassium Carbonate Analyses

	Sodium carbonate	Potassium carbonate
Na_2CO_3	97.1%	0.9% (max)
K_2CO_3	2.1%	98.0% (min)
K_2SO_4	0.6%	0.73% (max)
KCl	0.07%	0.15% (max)
Fe_2O_3	0.01%	0.005% (max)
residue	n.a.	0.1% (max)

Source: Minnes et al. (1983)

The nepheline slurry from the alumina consists largely of dicalcium silicate and is known as "bellite." The bellite is used in cement production and the chemical composition is shown in Table 12.

The bellite composes about 45% of the cement mix. It is combined with 49 parts (dry basis) ground limestone, four parts low grade bauxite, and two parts pyrite cinders and fired in a rotary kiln for the manufacture of normal type-one Portland cement clinker. The clinker is then ground in a ball mill with about 5% gypsum and about 15% dry bellite to produce a finished cement.

The indicated materials consumption and production (per tonne alumina) for the Volkhov plant is listed in Table 13.

Goryachegorsk Nepheline Syenite, U.S.S.R.

Large nepheline syenite deposits occur in central

Table 12
Typical Bellite Composition

SiO_2	31.5%
Al_2O_3	1.8%
Na_2O	0.9%
K_2O	0.3%
CaO	56.85%
MgO	1.27%
SO_3	0.34%
Fe_2O_3	2.7%
LOI	3.0%

Source: Minnes et al.(1983)

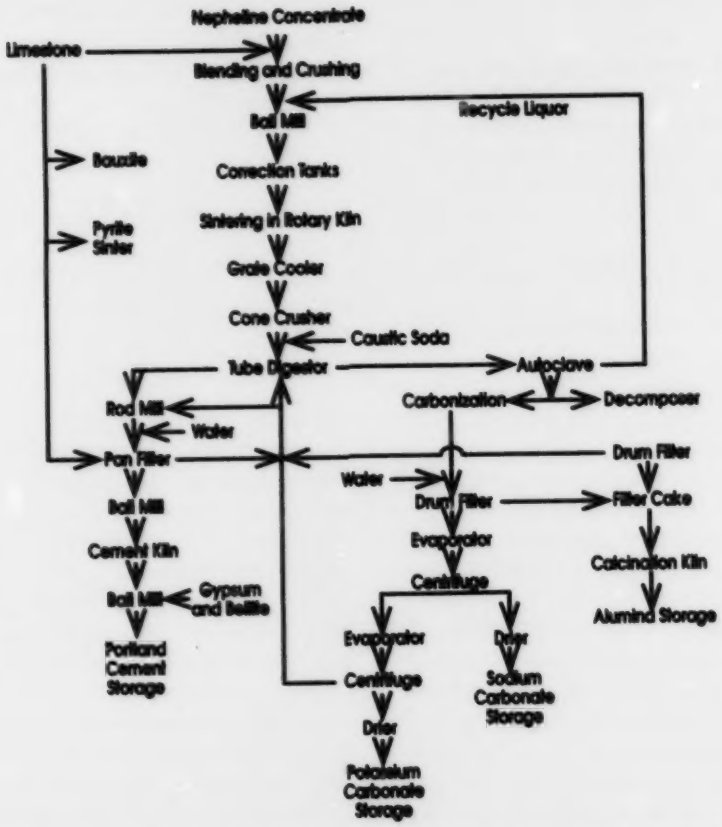

Figure 6. VAMI Lime Sinter Process for Production of Alumina, Alkali Carbonates and Portland Cement from Nepheline Concentrates (from Minnes et al. 1983).

Table 13
Materials Consumption and Production for the Volkhov Plant

Nepheline concentrate or rock	3.9 to 4.3
Limestone for alumina	6.0 to 7.8
for cement	5.0 to 6.0
Fuel (min 7000 kcal/kg)	
for alumina	1.67 to 1.7
for cement	1.3 to 1.6
Steam heat	4.68 to 4.1
Electric power	
for alumina	1050 to 119
for cement	700 to 860
Products:	
Alumina	1.0
Sodium carbonate	0.62 to 0.7
Potassium carbonate	0.18 to 0.2
Portland cement	9.0 to 11.0

Source: Minnes et al. (1983)

Siberia in the Goryachegorsk region. These deposits are mixtures of plagioclase feldspar and nepheline and are known as "theralite-syenites" in the U.S.S.R.. The deposits are mined by open pit methods and used for the production of alumina. The alumina plant is located at Achinsk, approximately 110 miles to the northeast. A typical chemical analysis of 22.6% Al_2O_3, 10.0% Fe_2O_3, 7.9% Na_2O and 1.5% K_2O has been reported for the Goryachegorsk nepheline syenite (Allen and Charsley 1968).

The nepheline syenite is beneficiated by magnetic separation to remove most of the iron. However, the lower alumina and alkali content of the material requires that a variant of the VAMI process be used to extract the valuable constituents. The silica in the Goryachegorsk ore is removed in an alkali-silica solution before sintering the nepheline residue with limestone. The colloidal silica is recovered from the alkali-silica solution. The nepheline-limestone sinter is processed in a caustic leach in a manner similar to the VAMI process. The Achinsk alumina plant recovers alumina, alkalis, and nepheline slurry for cement

Table 14
Product Mix from the Achinsk Alumina Plant Per Tonne of Alumina

Alumina	1 tonne
Caustic soda	300 kg
Potassium sulphate	100 kg
Nepheline slurry	6 to 9 tonnes

manufacture. The product mix per tonne of alumina produced is indicated in Table 14.

The nepheline slurry has the composition indicated in Table 15.

The nepheline slurry is used to produce a high early strength hydraulic cement. The cement is produced by grinding together the slurry (80 to 85% dry basis), 10 to 15% hydrated lime or quicklime, and 5% gypsum. The slurry contains about 30 to 35% water and the mixture is wet milled in ball mills and then dried at 500° to 600°C (Allen and Charsley 1968).

Bigwood-Rutter Nepheline Syenite, Ontario

CANMET applied the lime-sinter process to the sample extraction of alumina from the nepheline syenite deposit of Bigwood-Rutter in Ontario. Sample analysis of the rock was reported as follows (Table 16; Ripley 1979)

All the samples, were collected from surface outcrops; fresh unaltered rock was not studied. This is reflected in the atypically high iron values.

The high iron content had a negative effect on the yield of alumina. Using a slow-cool method, approximately 60% of the contained alumina was extracted. The sodium and potassium content of the nepheline syenite was recovered as the carbonates from the leach solution by carbonation. The recoveries of Na_2O and K_2O were 80% and 63% of theoretical values.

Table 15
Nepheline Slurry Composition at the Achinsk Alumina Plant

SiO_2	28.63%
Al_2O_3	3.13%
Fe_2O_3	4.80%
Na_2O	2.18%
CaO	52.97%
MgO	2.12%
TiO_2	0.30%
P_2O_5	0.48%
LOI	3.89%

Source: Allen & Charsley 1968

Table 16
Rock Analysis from the Bigwood-Rutter Deposit, Ontario

	Chemical Composition (weight %)
SiO_2	49.7
Al_2O_3	25.8
Fe_2O_3	11.3
Na_2O	8.2
K_2O	4.5
CaO	0.4
LOI	0.7

Anorthosite-Lime Sinter Process

The U.S. Bureau of Mines investigated a lime sinter-caustic leach technology for anorthosite (Edlund 1982). The chemical composition of materials is indicated in Table 17. The anorthosite contained 80 to 85% labradorite with minor perthite and hornblende.

Pellets for bench-scale sintering studies were prepared from mixtures of -200 mesh anorthosite with limestone and water. It was found that if the sintered pellets were cooled to 700°C, held there for 15 minutes and then cooled to room temperature, the phase transition from beta- to alpha-dicalcium silicate is accompanied by such a volume change that 95% of the mass falls ("dusts") to a -65 mesh powder. This helps to avoid grinding of the sintered pellets prior to leaching. Edlund (1982) reported that the weight ratio of limestone to anorthosite was critical in producing sinters with good "dusting" and leaching characteristics.

Table 17
Chemical Composition of Materials in Lime Sinter-Caustic Leach Technology

	% weight		
	Anorthosite		Limestone
	1	2	
SiO_2	56.6	53.0	0.8
Al_2O_3	27.6	28.8	0.4
Fe_2O_3	1.8	1.7	0.2
Na_2O	3.9	4.0	0.1
K_2O	0.9	0.8	0.1
CaO	11.8	11.9	53.6
MgO	0.3	0.1	0.5

Leaching of the sinter with 10% Na_2CO_3 at 60°C extracted 85 to 90% of the alumina in a product solution containing about 50g/L Al_2O_3. Research showed that leach residues left in contact with pregnant solution becomes a rigid gel, but prompt solids-liquid separation could avoid gelation. The presence of a calcium-sodium zeolite in the ungelled residues appeared to be the main difference with gelled residues.

The studies were not scaled up as the indicated operating costs were too high in comparison to the acid leaching processes for the extraction of alumina.

The anorthosite-lime sinter process was also investigated by CANMET in Canada (Hamer et al. 1978), using anorthosite from the Lac St. Jean region in Quebec. The sintering of crushed anorthosite and limestone was followed by leaching of the sinter product in sodium carbonate to liberate the alumina as aluminum carbonate. The alumina is precipitated as the hydroxide by CO_2 degassing and then calcined to yield alumina (Figure 7).

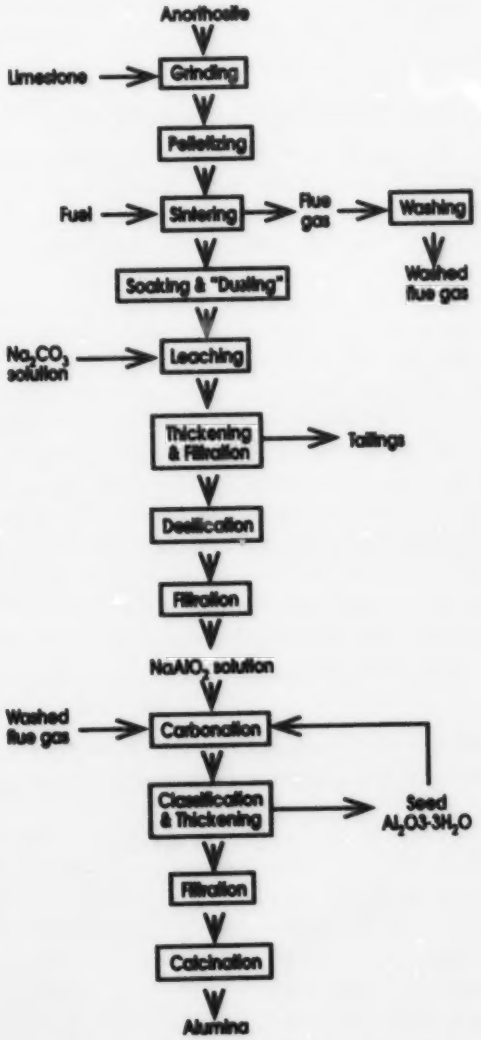

Figure 7. Proposed Lime Sinter-Caustic Leach Process for Production of Alumina from Anorthosite (from Barclay 1984).

Hamer et al. (1978), found that the maximum amount of alumina was extracted when the CaO/Al_2O_3 mole ratio was 2.6. The optimum conditions were reported as follows:

- sinter temperature 1300°C
- soak time 15 minutes
- fast cooling (1300° to 900°C in 1 hr)
- air quench
- leaching with 3 weight % sodium carbonate at 45°C for 30 minutes
- filter and rinse with water

The yield of alumina under these conditions was 94%. The lime-sinter process results in the large scale production of by-product calcium silicates and alkali carbonates, similar to the lime-sinter process used for alumina production from nepheline syenite. The process is energy intensive. Ready markets for the key by-products and a cheap source of energy would be necessary to make this process economically viable.

Anorthosite-Lime-Soda Sinter Process

In this process, sodium carbonate (soda ash) is added with limestone and the alumina source to the sintering mixture. A simplified flow sheet is shown in Figure 8. The additions of limestone and soda are controlled to give $Na_2O/Al_2O_3 = 1.0$, and $CaO/SiO_2 = 2.0$ to 2.2.

A modified process used by CANMET successfully extracted alumina from several Canadian anorthosites, including five in Ontario. Sodium carbonate is added to the sintering mixture in amounts calculated to yield the same basic conditions as the lime-sinter process, and to provide alkali oxides equivalent to 40% to 60% of the alumina in order to form alkali aluminates. This variation is termed the modified lime-sinter process in CANMET studies, and has generally given superior efficiencies for alumina extraction than the lime sinter process in the cases studied.

A key feature of these studies was that all the silica is balanced with twice as much lime, as it is the objective of the sintering procedure to form dicalcium silicate. Dicalcium silicate is insoluble in the sodium carbonate leach solution, together with alumina compounds that are soluble in this solution. Another significant advantage of dicalcium silicate in the sintered product is the decrepitation or "dusting" when cooled, avoiding the need for grinding prior to leaching.

The CANMET tests on Ontario anorthosite sam-

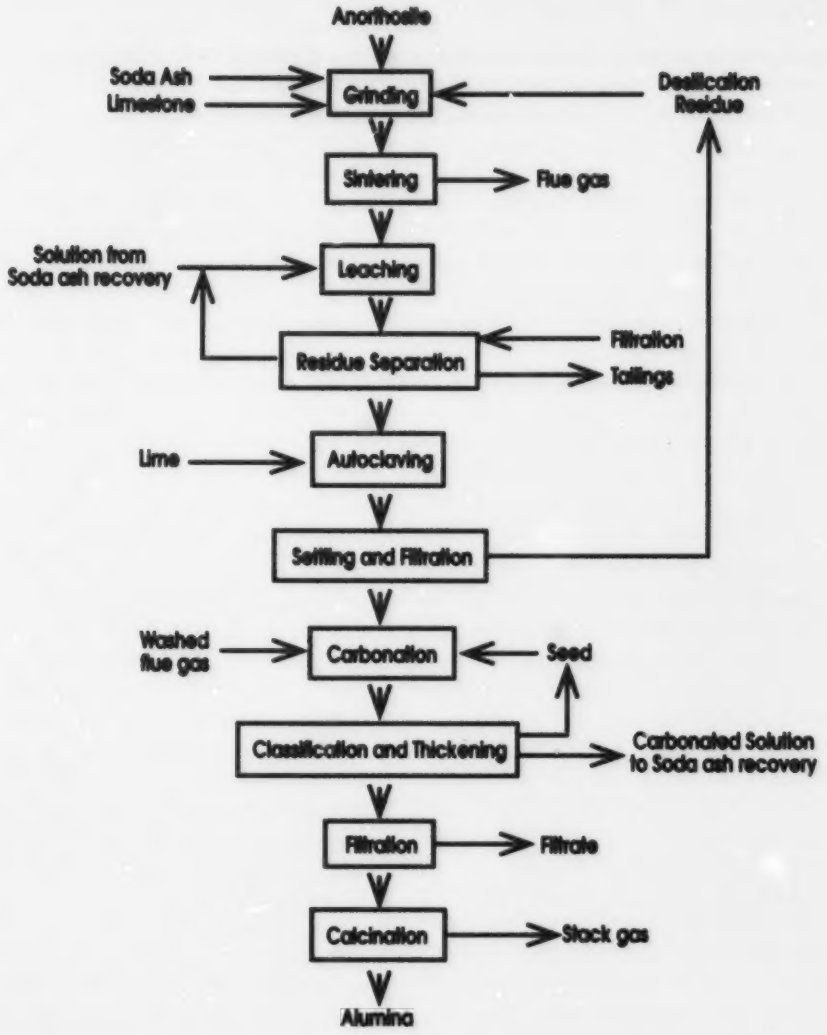

Figure 8. Proposed Lime-Soda Sinter Process for Production of Alumina from Anorthosite (from Peters and Johnson 1984).

ples, using the modified lime sinter process, gave yields of alumina extraction varying from 60% to 86% of the contained alumina. The chemical composition and alumina yields for the anorthosite samples is shown in Table 18.

The test conditions reported by CANMET (Ripley 1979a) were of an excess lime to excess alumina molar ratio of 2.5:1.0 and of an alkali ($Na_2O + K_2O$) to alumina ratio of 0.4:1.0. It was concluded that alumina extractions were lower in anorthosites with higher iron and magnesia contents, although it was recognized that there were also other undetermined differences among the alumina sources tested. Recoveries of alumina were inferior to the results obtained by acid leach processes.

Carbothermic Processes

Metallurgical grade alumina is one of the largest items in the cost of aluminum production. The direct use of unpurified ores in place of alumina are feasible in processes that combine reduction and purification. This could present opportunities for cost reduction if less costly ores can be used and/or commercial by-products can offset the production costs (Cochran 1987).

Pedersen Process

A carbothermic reduction process to yield a ferrosilicon alloy and an alumina slag was used in the earlier part of this century for purifying aluminous ores. A later improvement was the Pedersen process,

Table 18
Extraction of Alumina from Ontario Anorthosites by CANMET Modified Lime Sinter Process

Ontario Anorthosite	Chemical Composition (Weight %)									Alumina Extracted (Weight %)
	SiO_2	Al_2O_3	Fe_2O_3	TiO_2	CaO	MgO	Na_2O	K_2O	L.O.I.	
River Valley	45.77	30.90	4.39	0.10	14.28	2.40	2.31	0.17	0.21	23.8
Shawmere	44.90	34.02	2.24	<0.05	14.71	1.69	2.30	0.11	1.19	22.9
Parry Island	49.00	33.39	1.73	<0.05	11.66	0.41	4.21	0.43	0.51	27.5
Whitestone	49.20	30.90	1.97	<0.05	11.49	0.33	4.67	0.53	0.24	26.5
Wilkinson	47.13	21.83	7.63	1.40	12.10	1.76	4.35	1.29	2.02	13.01

* Calculated from chemical analysis for Al_2O_3 and per cent alumina extra

which was used commercially at Hoyanger in Norway from 1928 to 1969, when the operation was discontinued as non-competitive with large Bayer process plants. Although based on high-iron bauxitic ores, the Pedersen process is reported to be applicable to a wide range of aluminous materials and has been experimentally used for anorthosite. The process has been used in Sweden and the U.S.S.R. and has been tried on a pilot-plant scale in the U.S. (Kvande 1987). It is also reported that the process is used for two alumina plants in the People's Republic of China.

In the Hoyanger operations, a mixture of high-iron bauxite, limestone and coke was smelted in an electric furnace. Pig iron was produced as a commercial by-product, leaving a calcium-alumino-silicate slag rich in alumina. The slag was pulverized and leached with a sodium carbonate solution containing a small amount of sodium hydroxide, extracting a solution of sodium aluminate. Aluminum hydrate was precipitated from the solution by treatment with carbon dioxide gas from the smelting operation; the aluminum hydrate was then calcined to alumina (Kvande 1987; Cochran 1987).

Energy consumption in the Pedersen process is much higher than in the Bayer process, but it is a simpler process, as it does not use pressure digestion. It also yields by-product pig iron as well as high-quality alumina. It is also said that the capital requirements for commercial plant are much less than for a corresponding Bayer plant (Kvande 1987).

Processes for Aluminum-Silicon Alloys

Direct reduction of aluminous ores using carbothermic methods has been proposed as a route to aluminum-silicon (Al-Si) alloys. These alloys could subsequently be electrolytically separated to yield aluminum and silicon metal.

Landi et al. (1984) reported on the production of a raw Al-Si alloy by a one tonne/day pilot plant at Portoresme in Italy, using feldspathoid-bearing rock as the aluminous feed. Leucite ($KAlSi_2O_6$) was the feldspathoid used here. The rock was pre-treated through grinding to -3 mm and then magnetic separation was utilized to lower the iron oxide content below one percent. A typical analysis of the treated material is given in Table 19.

The aluminous feed was pressed into pellets in combination with a reducing agent having a high fixed carbon content (lithantrax), wood chips and a clay binder. The pellets were then charged into an ore reduc-

Table 19
Chemical Analysis by Weight %

SiO_2	53.80
Fe_2O_3	0.90
Al_2O_3	23.75
K_2O	15.80
Na_2O	1.85
CaO	0.62
MgO	0.22
MnO	0.12
TiO_2	0.11
P_2O_5	0.22
Other	0.45
LOI	1.18

tion furnace. The reduction process takes place at about 2200°C and consumes large amounts of electrical energy (16.195 kWh per kilogram of product).

The crude Al-Si alloy had a composition approximating 29 to 30% Al, 64 to 65% Si, 4 to 4.5% Fe and minor amounts of Ca, Ti, C and other impurities. The crude alloy is purified in an electric furnace. The process for raw Al-Si alloy is illustrated in Figure 9.

Similar work on direct reduction of aluminous ores, including anorthosites and syenites, was conducted by Alcan Aluminum Ltd. in the 1960s and early 1970s. While technically feasible, the processes were judged to be uneconomic in comparison to the Bayer process for the production of alumina and subsequent electrolytic reduction of alumina to aluminum by the Hall-Heroult process.

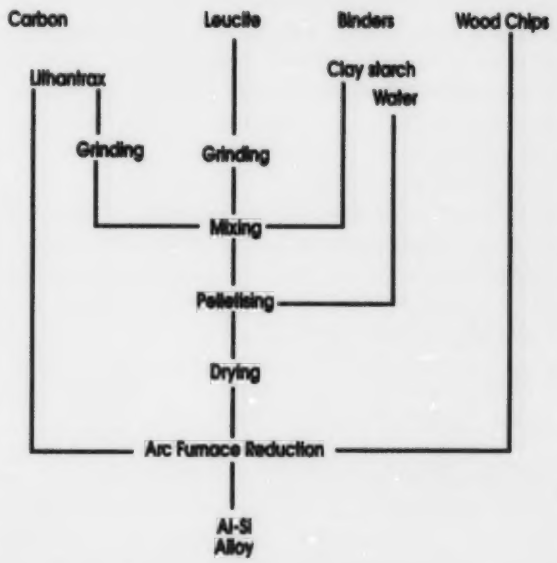

Figure 9. Proposed Direct Reduction Process for Production of Aluminum-Silicon Alloys from Feldspathoid-Bearing Rock (from Landi et al. 1984).

Chemical Product Uses

The formation of actual or potential commercial products from acid or alkaline processing is clearly dependent on such factors as the composition and mix of raw materials, reagents, additives and processing routes. It is recognized that such variables can provide a multitude of product options. The following section briefly sets out the uses of the product options mentioned in the foregoing review. All the notes, except for those on Portland cements, wollastonite and zeolites, are based on reports on inorganic chemicals for the Ontario Ministry of Northern Development and Mines by Law, Sigurdson & Associates (1988) and by Law, Sigurdson & Associates and SRI International (1990), published as Industrial Mineral Background Paper 11.

Aluminum oxide (alumina)

The impure hydroxide of aluminum, bauxite, represents the main raw material for alumina production at the present time. Bauxite can be used directly in the manufacture of chemicals, calcined to suitable abrasive or refractory grades or subjected to the Bayer Process to remove silicon, iron, titanium and other impurities, thereby producing an alumina trihydrate (ATH) containing sodium oxide as the dominant impurity. The ATH may be calcined for use in aluminum metal production or as specialty calcined aluminas, sold as trihydrate or converted into activated alumina.

Approximately 90% of the alumina produced is used in the manufacture of aluminum. In non-aluminum consumption, a large fraction of ATH (over 400,000 tonnes per year in North America) is utilized in the manufacture of aluminum chemicals (aluminum sulphate, sodium aluminate, aluminum fluoride and synthetic zeolites). Additional tonnages are ground to grades useful as a flame retardant for plastics, carpet-backing and building board or as a pigment for paint, rubber, plastics and paper.

Almost 300,000 tonnes of ATH together with large tonnages of calcined bauxite are consumed annually in North America as specialty aluminas such as activated alumina and specialty calcined products for non-metal applications. Activated alumina is used as a catalyst, catalyst support, dessicant and process scavenger. Non-metal uses of calcined alumina include refractories, abrasives, ceramics, whitewares, glass and enamels. The ATH can also be converted to tabular (sintered) and fused aluminas. The tabular form goes into refractories, ceramics, molten metal filter media, ground filler for epoxy resins, inert supporting beds for adsorbents and catalysts and heat exchange

media. The main use for fused alumina is abrasives. Another specialty alumina is alumina monohydrate, which has efficacy in catalysts, premium abrasives and binder.

Catalyst production requires alumina, but the production of catalysts in Canada often entails the importing of pre-treated alumina. The large surface area, pore structure and surface chemistry of activated alumina combine to make it useful as a hydrocarbon desulphurization catalyst, an alcohol dehydration catalyst, a hydrocarbon isomerization catalyst (either activated alumina or silica-alumina), a catalyst support for automotive catalytic mufflers as well as for petroleum hydrorefining and gasoline reforming and cracking. Activated alumina is also a dessicant for the drying of process streams.

Alumina constitutes varying proportions of the silica-type fluid catalytic cracking catalysts, which in North America is more than a $300 million per year market. Additional ATH is consumed in the manufacture of the organo-aluminum catalysts.

Aluminum sulphate (alum)

Aluminum sulphate is usually produced by direct reaction of bauxite or clay with sulphuric acid. Pure ATH is necessary as the aluminum source if the object is to make an iron-free aluminum sulphate, as is the case for applications in food, pharmaceuticals, textile dyeing and high-quality paper.

The very simplicity of the process and the need to have regional plants to justify supply of a low-value material in water solution means that there are 80 to 85 alum plants in North America.

Well over half the alum ends up in pulp and paper. Whatever is not used for the precipitation of rosin size is required for treatment of the process and/or waste water. The other major application for alum is as a coagulant/flocculant in municipal and industrial water and wastewater treatment plants. Aluminum sulphate has relatively small, miscellaneous applications in cosmetics and soap manufacture, cellulosic insulation, manufacture of chemicals, concrete modification, grease manufacture, fire-extinguishing solutions, leather and tanning, and specialty applications in the food industry.

Aggregate demand for alum has been falling steadily over the past twenty years and appears to be stabilizing at about 1 million tonnes per year in North America. The move to alkaline papermaking will accelerate the decline.

Calcium nitrate

Calcium nitrate is a highly deliquescent salt often referred to as lime saltpetre. It is used (especially in Europe) as an artificial manure, either directly or after conversion to ammonium nitrate. With ammonium nitrate so readily available in North America, calcium nitrate has only a limited application in agriculture. Other uses for calcium nitrate include pyrotechnics, explosives, matches and incandescent gas mantles. It is also employed in the manufacture of radio tubes. Calcium nitrate is also a coagulant for rubber latex. Other nitrates can be derived from calcium nitrate

Calcium silicates

A synthetic calcium silicate is at times selected as a reinforcing filler for rubber and similar compositions are used as absorbents and decolourizing agents.

Portland Cements

Portland cement is produced by an accurately-proportioned mixture of calcareous material and a source of silica and alumina. The fused "clinker", a complex mixture of calcium silicates and aluminates, is mixed with gypsum (4 to 5% by mass) and pulverized to a fine powder to form the cement. At this stage, up to 5% limestone may also be included as an additive for some Portland cements.

Portland cement is among the most widely used construction materials in the world, with annual North American production totalling more than 90 million finished tons in 1988. More than twice as much Portland cement is used in construction than the total of all other materials, including wood, steel, plastic and aluminum (Institute for Research in Construction and Matex Consultants Inc., 1990).

Portland cement is the principal binder used in concrete and finds applications in masonry cements and in the manufacture of numerous building products, including bricks and blocks; cladding; drain and water pipes; and roofing, or as a binder for other minerals in such products as asbestos cement sheet and pipe.

By close control of materials and process, 5 basic types of Portland cement are produced by Canadian cement producers. In the U.S., there are 38 various types of cements, which include eight different types of Portland cement (more than 95% clinker) and Portland cements incorporating various levels of supplementary cementing materials used as mineral admixtures.

Potassium carbonate

The glass industry is the largest consumer of potassium carbonate. As the fluxing agent or in blends with lead, soda ash or other fluxing agents, it contributes to the lustre, clarity, "ring" and other characteristics associated with quality glassware. It is also used in the

manufacture of flintware, optical glass, television tubes, electronic and neon glass and tubing and any glass applications requiring superior brightness. In ceramic coatings, enamel frits and ceramic glazes, potassium carbonate makes colour modifications easier. In titanium enamels it can improve low temperature coverage.

The high purity and reactivity of potassium carbonate leads to its use in producing a wide variety of potassium chemicals (phosphate, silicate, oxalate, citrate, acetate, gluconate, bromide, bromate, etc.) and drugs. Potassium carbonate also has application in foods. In chocolate and cocoa manufacture, the chemical neutralizes some organic acids to improve the flavour, darken the appearance and make a more soluble product. Potassium carbonate reacts with fatty acids to form liquid soaps. Agricultural applications represent an expanding outlet. Some gas processing plants employ potassium carbonate as the absorbent for carbon dioxide in the cleaning up of raw gas.

Silica Gels and Sols (colloidal silica)

Amorphous silica hydrogels are manufactured commercially from soluble silicates. A continuous gel forms by condensation of the hydrated colloidal particles when the alkali is neutralized. Aerogels are made by treating the crude hydrogel with alcohol to remove the water, displacing the alcohol with air by heating in an autoclave and then releasing the pressure. Aerogels are lighter and fluffier than hydrogels because shrinkage of the gel structure on drying has been eliminated.

The paint industry is the leading consumer of silica gels. Their chief function is that of a flatting agent in clear lacquers and varnishes and in pigmented coatings.

Silica sols, aqueous colloidal silica suspensions, were developed in the early 1960s and are prepared with activity levels of 20, 30 or 50% silica. Their major applications are as a binder in investment castings, in paper processing and coating, in silicon water polishing and as a binder in refractories.

The paperboard industry is a very large consumer of colloidal silica as a surfacing material. Colloidal silica is the inorganic constituent of two multicomponent retention-aid systems used in papermaking. With the trend towards increased use of neutral or alkaline papermaking techniques in North America, demand for colloidal silica as a component in fibre-retention systems is expected to increase.

The North American market for colloidal silica reached approximately 14,000 tonnes in 1988.

Sodium Aluminate

Aluminum trihydrate dissolved in caustic soda yields sodium aluminate. Some 50 to 60% of the North American demand for sodium aluminate ($NaAlO_2$) is met by captively-produced product. The largest captive use is in the manufacture of sodium aluminosilicates, also known as synthetic zeolites. These are primarily used in detergents (dry formulations only), with other uses as catalysts (chiefly FCC catalysts) and as adsorbents/dessicants.

Merchant sodium aluminate is principally used in competition with alum (aluminum sulphate) in water treatment and the papermaking industry.

Total consumption of sodium aluminate was 161,000 tonnes in 1987 in North America.

Sodium Aluminum Silicates

Synthetic sodium aluminum silicates (SSAS) have been traditionally used as fillers and extenders in paper, paint and rubber applications as well as carriers and free-flowing agents in foods, liquids and chemicals. Some SSAS products constitute intermediates in synthesis of certain chemical specialties.

These silicates are prepared by the reaction of aluminum sulphate with sodium silicate. The insoluble, white precipitate of the SSAS product is filtered, washed, dried and milled to the desired degree of fineness.

Sodium carbonate (soda ash)

Although synthetic process soda ash facilities still dominate in Europe, Japan, Canada and other parts of the world, U.S. production has been naturally-derived material for many years. Trona ore deposits in southwestern Wyoming constitute the largest source of sodium carbonate in North America. The aggregate capacity of the five mines at Green River is 9 million tonnes. There is additional capacity at Searles Lake in California.

Though soda ash is widely used as an alkali, glass manufacturing is by far the largest application (about half of the total 7.5 million tonnes consumed annually in North America). Soda ash is also a source of sodium ion and alkalinity in making sodium phosphates, sodium silicates, sodium chromates, sodium bicarbonate and other compounds. In detergents, soda ash is used as a builder in low-phosphate and non-phosphate detergents; the recent demand for liquid detergents may adversely affect the production of powders and the future demand for soda ash. Other uses of soda ash include water treatment, wood pulping and flue-gas desulphurization. Flue-gas desulphurization

has potential for growth as a market application, technology such as solid injection is still under development.

Sodium Silicates

Synthetic sodium silicates are usually manufactured by fusing sodium carbonate and specially selected silica sands at high temperatures. The ratio of sand to the soda ash determines the type of silicate produced and its degree of alkalinity. Solid sodium silicates are also produced via fusion, in which case the sodium source may be caustic soda rather than soda ash. Some sodium silicates are obtained as a by-product during the manufacture of zeolite fluid cracking catalysts from kaolin. The conversion of zircon sand to zirconium oxide can yield by-product sodium silicate as well.

Because sodium silicate is a relatively low-value product most often sold in solution form, its supply is usually regional in nature in order to minimize transportation costs. In the U.S., for instance, the leading merchant suppliers operate a number of plants across the continent.

The fastest growing markets in Canada are the bleached groundwood mills (the silicate stabilizes the hydrogen peroxide brightening agent). Silicate consumption in mechanical pulping is already close to 25,000 tonnes per year and should exceed 60,000 tonnes per year by 1990 (as 41-Baume solution).

Silicates are also employed as adhesives, detergents and detergent builders, cleaning compound ingredients, cement binders, sizes, protective coatings and films, coagulant aids for water treatment, rust inhibitors, catalyst bases, deflocculants and in the manufacture of zeolites and precipitated silica. U.S. demand for sodium silicates is now greater than 350,000 tonnes per year (anhydrous basis). Canadian usage is proportionately higher (125,000 tonnes per year or thereabouts) because of the strong demand for silicates in the resource industries (mining as well as pulp and paper).

Wollastonite (synthetic)

The theoretical composition of wollastonite is 48.3 weight % CaO and 51.7 weight % SiO_2. Synthetic wollastonite has been intermittently produced in Europe over the last two decades, and an estimated total of approximately 25,000 tonnes was produced for the European market in 1989. (Brodmann et al. 1991).

Synthetic wollastonite products generally exhibit lower trace impurities than natural wollastonite, notably in sulphur, phosphorous and iron content. High chemical purity and purity consistency are essential requirements for metallurgical uses, such as in metal casting powders and in welding rod fluxes.

Wollastonite has applications in a wide range of whiteware ceramics. It is one of the raw materials suitable to formulate compositions for modern fast-firing techniques because of the good attributes that it confers to ceramic bodies, low shrinkage, high bending strength, uniform dilatometric behaviour and low moisture expansion (Ibanez et al. 1990). Very low-iron synthetic grades are used in the production of water-insoluble white glazes or glaze frits (Brodman et al. 1991).

Zeolites (synthetic)

Over 150 types of zeolite structures have been synthesized to precise specifications to use their unique properties in cation selectivity (molecular sieve effect), high cation exchange capacity and their adsorption of water and gases.

They have large, well-established markets as catalysts in the petroleum and petrochemical industries. The first synthetic molecular sieve zeolites were commercialized in 1954 and adopted not long afterwards in cracking catalysts for use by petroleum refiners. They are also valued in the chemical industry for gas separation and purification and for the drying of gases and organic liquids. Zeolites are added to powder detergents to displace phosphates for water softening. Zeolites have important applications as well in water treatment, such as ammonium removal from effluents, removal of cesium and strontium ions from nuclear waste waters and heavy metal removal from mining/metallurgical wastes. They are effective adsorbents for oil and grease spills.

In agriculture, zeolites are used as slow-release carriers for pesticides, chemicals and cationic nutrients; other applications include anti-caking and dessicant use in agricultural chemicals and feed.

Newer uses in the energy sector include the catalytic conversion of organic chemicals such as methanol to high octane fuels and as a heat storage medium for solar heating/cooling.

Conclusions

Ontario is a well-established supplier of mineral products from nepheline syenite, principally for the glass and ceramic industries and for filler and extender markets. No significant product innovations are anticipated from the dry separation techniques that have been used and refined in the province for over fifty years. Additional processing, however, to produce surface-treated grades of micronized fillers is an option for research; specialty markets may be available if the performance of such fillers, after modification, could be appropriately enhanced in polymer resins.

Mineral processing by flotation methods, in conjunction with magnetic separation, is an alternative that may be attractive for some nepheline syenite deposits. The primary product line could be broadened with the separation of a nepheline concentrate and a feldspar fraction. The ability to segregate non-magnetic minerals may expand the selection of ore and, in some cases, provide an additional mineral by-product such as corundum.

Anorthosites are also suitable for both dry and wet processing methods for lime feldspar products. Changes in ceramic manufacturing technologies in recent years, such as the development of the fast-firing process, may warrant a revised assessment of the potential use of high-calcium anorthosite products for specific applications.

Research on digestion processes with mineral acids has favoured the anorthosites, rather than the syenites, for their higher alumina content. Anorthosites with a high calcium content and low Si:Al ratio are readily amenable to acid treatment.

Acid digestion processes developed by Alcan Aluminium Ltd. in Canada (hydrochloric acid — calcium chloride leach — gas sparging) and by the U.S. Bureau of Mines (fluoride-assisted hydrochloric acid leach — gas sparging) show promising recoveries of alumina and product purity for potential development. Acid processing can also provide other product options, including aluminum sulphate, calcium sulphates, calcium nitrates, calcium silicates, specialty silicas and sodium aluminates. Feldspathoids such as nepheline are particularly suitable for the synthesis of zeolites.

The leaching of feldspathoids by organic acids is only at an early stage of research; the method merits further investigation as a potentially low-cost, environmentally attractive approach.

Sintering processes have been studied for the extraction of alumina from anorthosites and nepheline syenites. A lime sinter process, similar to that employed in the U.S.S.R. for alumina production from nepheline-bearing ores, would provide sodium carbonate (soda ash), potassium carbonate and large quantities of Portland cement to be marketed as well.

Carbothermic processes for the direct production of aluminum or aluminum silicon alloys from unpurified ores can use different aluminous ores. The higher-alumina bauxites, unless they are prohibitively priced, would remain preferable as ore sources to lower-grade anorthosites.

Historically, much of the research effort in acid and alkaline processes has been directed to obtain a cell-grade alumina (for aluminum production) from non-bauxite sources. There are, however, significant markets for other alumina grades and aluminum chemicals that can be obtained from anorthosites or nepheline syenites; this was demonstrated by the recent commercial entry of a producer of aluminum sulphate from acid-treated anorthosite in Finland. Similar opportunities may occur for an Ontario producer to serve a strong regional market for chemical products from high-alumina rock resources. The viability of such opportunities is likely to depend not only on the competitiveness of the primary product, but on the aggregate value of marketable by-products as well.

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3. Review of High-Alumina Rock Deposits in Ontario

Discussion

Anorthosites

Property-scale reports are provided for 22 anorthosite occurrences across Ontario (see Maps 1 and 2). These bodies are: Allsaw, Arnstein, Eau Claire, Elbow, Fall Lake, Farquhar, Head River and Smudge Lake, Mercer, Little Lake, Moon River and Twelve Mile Bay, Parry Island, Percy, Pickerel, Raganooter, Red Deer, River Valley, St. Charles, Whitestone, Wilkinson, Bad Vermilion, East-Bull and Shawmere anorthosites. Certainly with respect to Al_2O_3 content, anorthosites have high potential. Chemical analyses showed anorthosite samples from many of these bodies with Al_2O_3 values consistently above 25 weight %. The Allsaw, Arnstein, Raganooter, Moon River, Percy, Bad Vermilion and Shawmere anorthosite samples have the highest Al_2O_3 values (between 27 and 29% on average). In some of these cases, however, selective sampling of high feldspar rocks gives the impression of higher Al_2O_3 bulk compositions. Total alkali content ($CaO+Na_2O+K_2O$) is less variable on the whole but anorthosite samples with the highest values (16 to 18%) are the Allsaw, Arnstein, Raganooter, Little Lake, Moon River, Parry Island and Percy bodies. Scapolitization probably accounts for high CaO values (12 to 13 weight %) in the Allsaw Anorthosite (Easton personal communication). Total alkali content commonly ranges between 12 and 18% in the anorthosites.

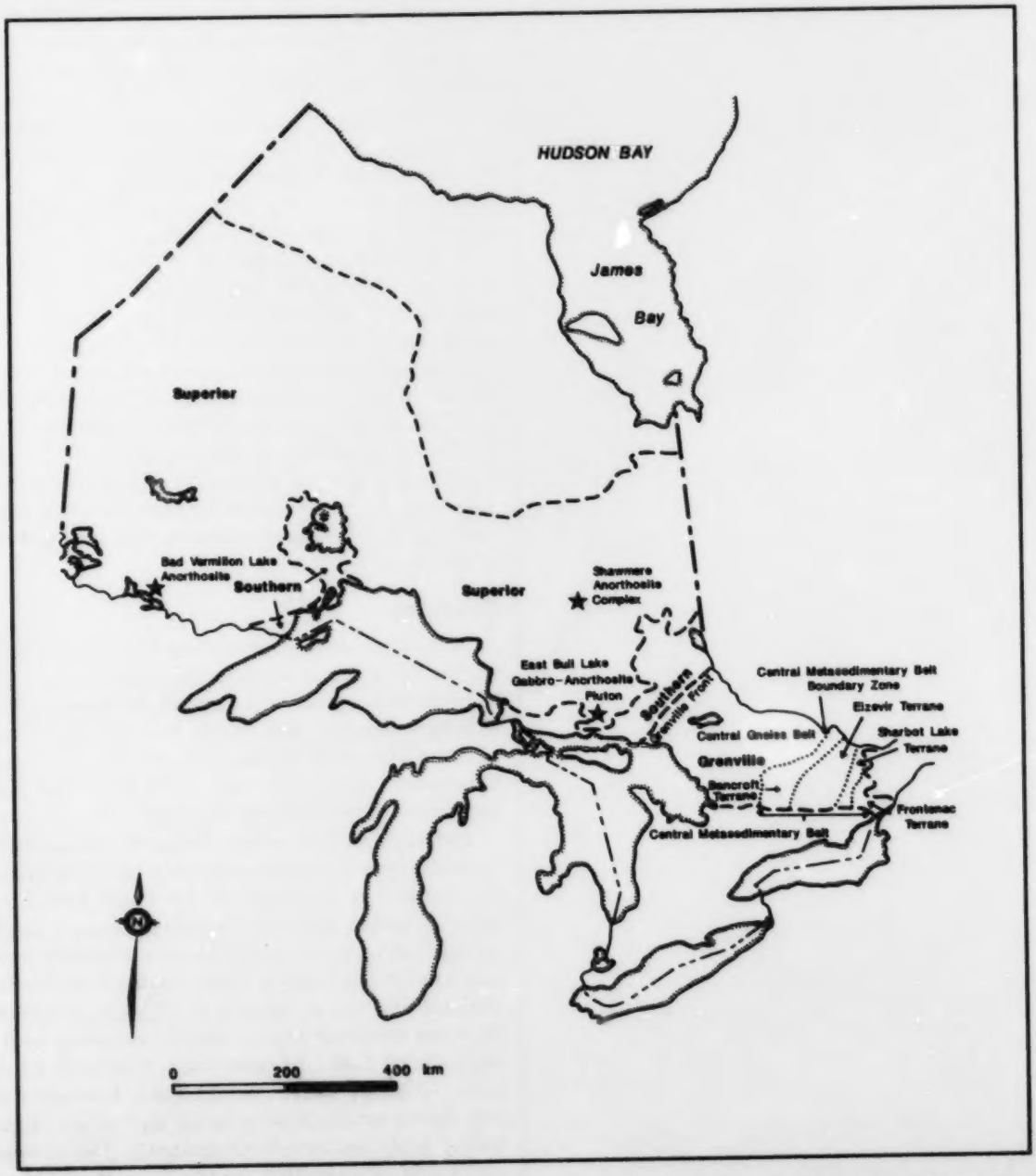
Syenites

Property-scale reports of 13 syenite and nepheline syenite occurrences are presented (See Map 3). The Bigwood-Rutter, Callander Bay, Gooderham Belt, Tory Hill Belt, Bancroft Belt, Wolfe Belt, Renfrew County, Blue Mountain, Gawley Creek, Mount Moriah, Skootamatta, Burns Lake and Mount St. Patrick syenites occur in the Grenville Province.

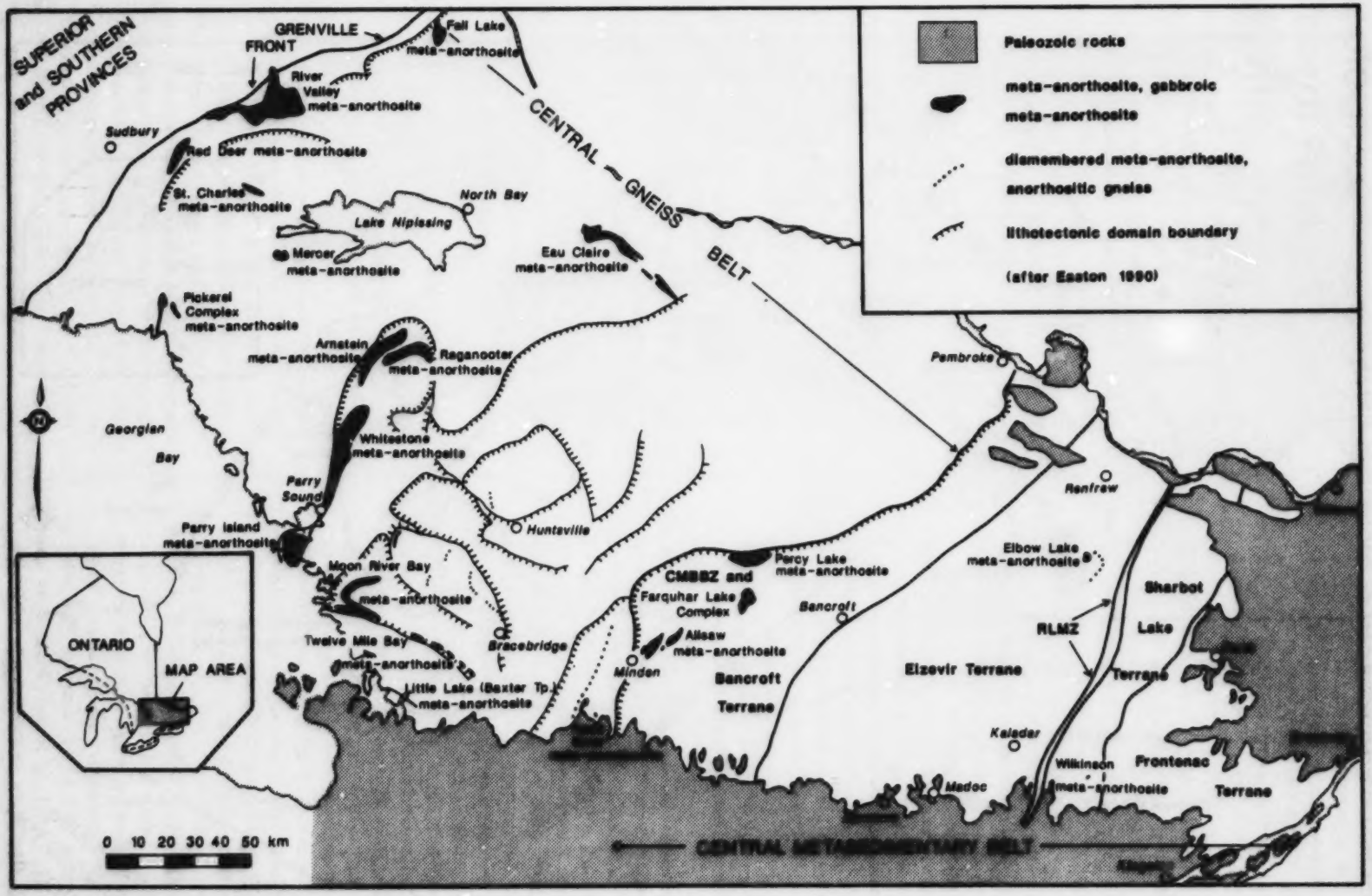
Although studies concentrated on the Grenville Province syenite occurrences, there are many syenite occurrences in the Superior Province which may deserve further attention. Secondary syenite targets include the Lebel Township Syenite, McElroy Township Syenite and the Otto Stock. Higher mafic content and heterogeneity of these bodies (Currie 1976) make them less attractive targets. Alkalic complexes such as the Poohbah Lake, Sturgeon Lake, Coldwell, Killala Lake, Chipman Lake, Herman Lake, Lackner Lake and Nemegosenda Lake contain significant syenite and/or nepheline syenite components. The commercial value of nepheline syenite from the Coldwell Complex has been tested but studies concluded that

iron-rich inclusions rendered the material unusable. These alkalic complexes share many characteristics and are worthy of further consideration to evaluate the extent of syenite/nepheline syenite units and to characterize the mineralogy of these bodies. Production constraints for this report have not allowed for research of these secondary targets.

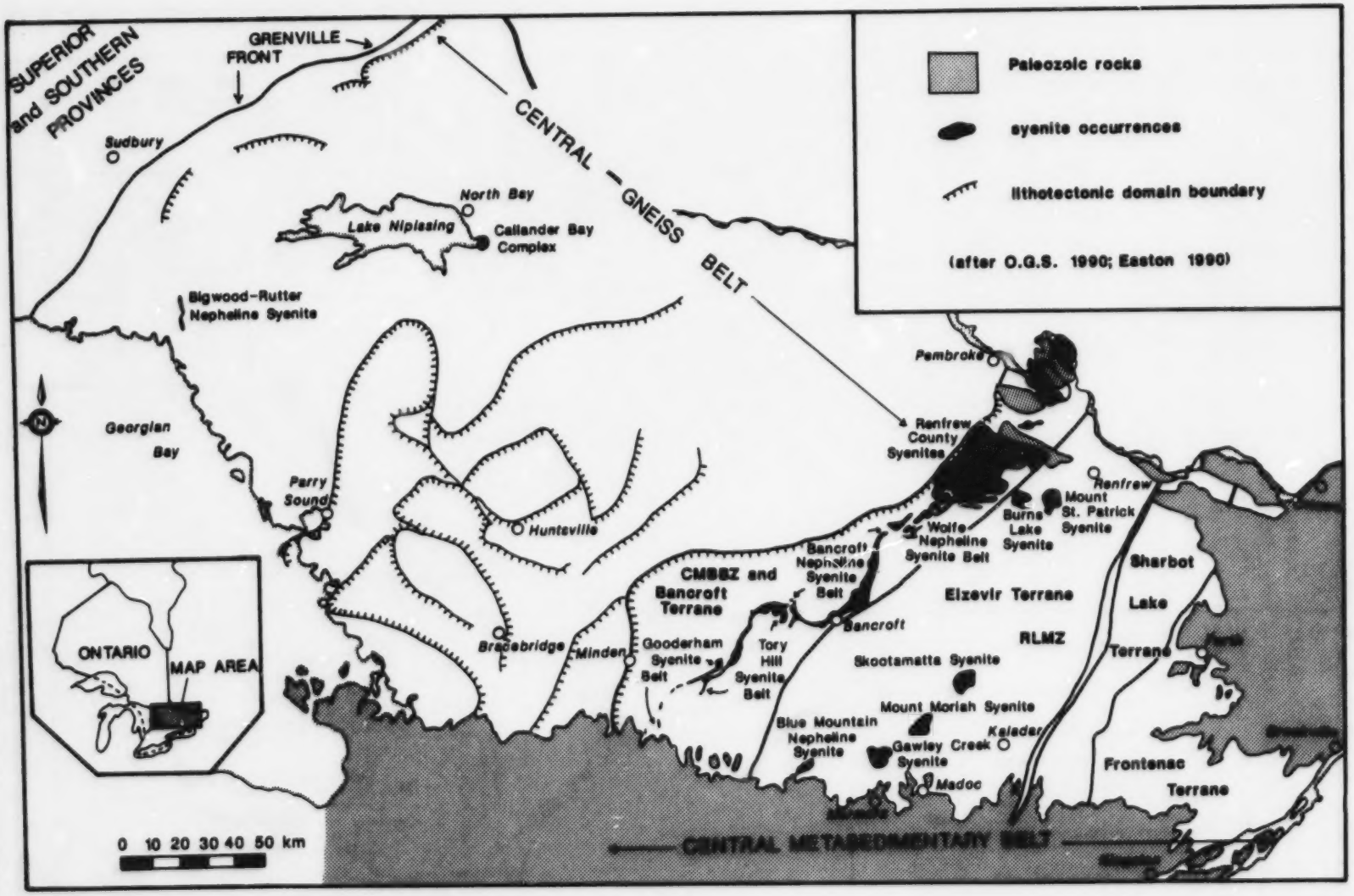
Syenite analyses, where available, show lower Al_2O_3 values than that found in anorthosites, typically closer to the 20% cutoff mark. The presence of nepheline (+ corundum) however, particularly in the belt-type occurrences and the Blue Mountain Syenite, increases Al_2O_3 values to between 23 and 27 weight %. Total alkali content in syenites is comparable to anorthosite analyses except that in most syenites, Na_2O instead of CaO (as in anorthosites) dominates, normally comprising two thirds of the total alkalies.



Map 1. Superior Province Anorthosites and Major Subdivisions of the Geological Provinces.



MAP 2. Anorthosite Occurrences in the Grenville Province of Ontario.



MAP 3. Syenite Occurrences in the Grenville Province of Ontario.

Geological Factors in Mineral Product Potential

There are several geological factors which affect the quality of the feldspar and felspathoid minerals as well as the alumina and alkali potential of a given occurrence. Marmont and Johnston (1987), Marmont (1988) and Marmont et al. (1988) have outlined several geological criteria which can aid in the search for prospective anorthosite bodies. These criteria can also be applied to syenites, nepheline syenites and nepheline gneisses. Some of these factors are summarized below.

1) *Purity of the feldspar*: The purity of feldspars is controlled in many cases by the degree of recrystallization a body has undergone. Commonly feldspar grains initially form with inclusions, which can seriously affect the quality of a feldspar product. Inclusions can increase the iron content, and darken the colour of the feldspar product. The inclusions are also difficult or impossible to remove and are therefore an undesirable component in many feldspar applications (e.g., fillers, glass and ceramics raw materials). The process of recrystallization, if intense enough, can remove inclusions from feldspar grains, resulting in purer feldspar grains. The colour of an anorthosite can indicate the degree of recrystallization. Generally the whiter a rock the more intensely recrystallized it is. An anorthosite with cloudy, grey or black feldspars is probably inclusion-rich.

   Iron-titanium oxide inclusions are common in the Whitestone, Fall Lake, Mercer, River Valley, and Red Deer anorthosites. Pyroxene inclusions have been observed in nepheline of the Bancroft Nepheline Syenite Belt. Significantly recrystallized or partially recrystallized anorthosites include the Arnstein, Elbow, Little Lake, Moon River, Percy, Raganooter, Whitestone and Shawmere bodies.

2) *Deformation*: The degree and styles of deformation can affect industrial mineral potential in different ways. The presence of shear zones often results in the introduction of undesirable components such as hematite (Fe), or sulphides (pyrite, chalcopyrite, etc.) as in the East Bull Lake Intrusion. The Percy Lake Anorthosite contains a network of anastomosing shears, spaced from several metres to tens of metres apart (Marmont et al. 1988). Depending on the spacing and abundance of shears, extraction can avoid these zones.

   Brittle deformation can produce fractures along which alteration and subsequent mineralization (e.g., sulphides, oxides) are concentrated as in the East Bull Lake Intrusion, which contains pyrrhotite, chalcopyrite and pyrite along shears (Moore and Armstrong 1943). The addition of certain elements can contaminate and negatively affect recovery of a feldspar concentrate. Feldspar potential may be depleted where deformation results in grain size reduction, since some commercial applications have minimum grain size requirements.

   Judging from previous studies done on the Coldwell Complex nepheline syenite (Assessment Files Research Office, File 63A.405) the presence of iron-rich mineral inclusions in feldspars and nepheline, may present the most serious problem with regard to potential. Keeping this in mind, the more recrystallized bodies, particularly the Allsaw, Raganooter, St. Charles and parts of the Whitestone, River Valley and Shawmere anorthosites represent the best targets.

3) *Alteration*: The formation of nepheline is in many cases attributed, at least partially to metasomatism. Nepheline contributes Al_2O_3 to the bulk rock composition. Conversely, alteration of feldspars could reduce the potential by introducing iron or other undesirable components. The most common feldspar alteration products in the anorthosites and syenites are sericite, scapolite and epidote. Chlorite alteration is observed in the Bad Vermilion Lake and the St. Charles anorthosites. These types of alteration usually result in finer grained fibrous minerals replacing cores of feldspars and sometimes pervasive alteration can result in 40 to 90 % modal scapolite. Although alumina and alkali content may remain high, the effect scapolite has on mineral processing would have to be studied in these cases.

4) *Xenoliths, veins and dikes*: Undesirable material such as xenoliths, dikes and veins contribute to the amount of waste, lower the grade and complicate extraction. The East Bull Lake body contains up to 20% volume dike material (McCrank et al. 1989). Alteration minerals such as chlorite, amphibole, epidote,

pumpellyite, laumontite, and calcite result from pervasive greenschist metamorphism, infill abundant fractures and joints in the East Bull Lake body (McCrank et al. 1989).

5) *Textures*: Mineral textures such as sutured and lobate grain boundaries, intergrowths, and fine or variable grain size can complicate separation of a feldspar concentrate. Fine-grained rocks at the sheared base of the Allsaw Anorthosite and serrated grain boundaries in parts of the Mount Moriah Syenite are examples where textures may negatively affect mineral potential.

The Blue Mountain Nepheline Syenite represents a pure source of nepheline syenite which could have good alumina and alkali industrial mineral potential outside of its present use in the glass, ceramics and filler applications. The Percy Lake Anorthosite, if feldspar proportions are high enough, may represent a feasible target.

The Gawley Creek, Mount Moriah, Skootamatta, Burns Lake and Mount St. Patrick syenites are poorly known, but medium- to coarse-grained, predominantly massive textures and relatively homogeneous nature of these bodies make them favourable targets for further investigations. Unfortunately, these bodies are not well studied and chemical data is sparse or unavailable.

Anorthosites of the Central Gneiss Belt are troctolitic in composition (olivine bearing) (Lumbers, personal communication), and may have a higher mafic content than the anorthosites of the Central Metasedimentary Belt. As well, zones rich in iron-titanium oxides may negatively affect the potential of several of these bodies (i.e., Fall Lake, River Valley, Red Deer anorthosites). Anorthosites in the Parry Sound area are less gabbroic than anorthosites in the Central Metasedimentary Belt (Farquhar and Percy Lake anorthosites) and could represent the most favourable feldspar targets.

In summary, feldspar potential is good in anorthosites and syenites of Ontario. High CaO plagioclase feldspars dominate the anorthosite mineralogy and alkali and perthitic feldspars dominate the syenite mineralogy. Alumina content is highest in the anorthosites. Total alkali content is slightly higher in the anorthosites than syenites and syenites are more suitable in applications which demand a low CaO content.

Geological Settings in Ontario

The following brief overview of the geological provinces serves to explain the general geological setting of anorthosite, syenite and nepheline-bearing occurrences in Ontario.

Anorthosite and syenite occurrences of Ontario lie within the Superior and Southern Provinces in the north and within the Grenville Province in the south. The two geological provinces are separated by a northeast trending boundary zone, situated 15 to 20 km southeast of Sudbury (see map 1). This boundary zone is referred to as the Grenville Front Tectonic Zone, and is characterized by a group of highly deformed and metamorphosed rocks.

The Archean Superior Province consists of granite-greenstone, metasedimentary and metaplutonic terranes. Anorthosites occur most commonly in association with gabbroic intrusions, near or within greenstone belts as is the case of the Bad Vermilion Lake Anorthosite. There are many Archean layered anorthosite/gabbro bodies in the Superior Province which fit into this group e.g., Lac Des Isles Complex and Big Trout Lake Gabbro Anorthosite. Similar bodies such as the Crystal Lake Gabbro belong to the Proterozoic Southern Province. Although the proportion of gabbroic material is higher in these bodies than in the Bad Vermilion Lake body for instance, they may deserve consideration as secondary targets. It was decided at an early stage of this project that the least mafic bodies would be more suitable for consideration.

The Shawmere Anorthosite Complex lies within the Kapuskasing Structural Zone, an area of intense deformation and metamorphism. Although it is generally agreed that the Shawmere Complex is Archean (about 2700 Ma) in age, there is some controversy over the exact age (Percival and Krogh 1983).

The Proterozoic East Bull Lake Pluton intrudes rocks of the Superior Province and although similar in composition to the Archean gabbroic bodies, it has been considered comparable with anorthosites just south of the Grenville Front (Easton, personal communication).

Nepheline syenites occur in association with syenite stocks and as constituents of alkalic complexes. Both of these types of intrusions are spatially related to fault systems (Currie 1976) throughout the Superior Province of Ontario. The Otto Stock, Lebel Stock and McElroy Stock are all associated with the Kirkland Lake-Larder Lake Break. The Otto Stock and the Callander Bay Alkalic Complex were studied in detail

however, these bodies probably have lower potential as feldspar resources. Syenites and nepheline syenites of alkalic complexes represent secondary targets and are not described here.

The geology of the Grenville Province of Ontario is more complex. In Ontario, the Grenville Province is subdivided into the Central Gneiss Belt immediately south of the Grenville Front, and the Central Metasedimentary Belt further to the southeast (refer to Maps 1, 2 and 3). The Central Gneiss Belt is subdivided into several structural domains and subdomains. Anorthosites are more common in this area than elsewhere in the Ontario, with the majority being situated along shear zones near the boundaries of the Parry Sound Domain, e.g., the Arnstein, Whitestone and Parry Island anorthosites which occur along the west margin of the Parry Sound Domain and the Parry Sound Shear Zone.

The northern Central Gneiss Belt anorthosites are the Fall Lake, River Valley, Red Deer, St. Charles, Mercer, and Eau Claire anorthosites. The southern Gneiss Belt anorthosites are the Arnstein, Raganooter, Whitestone, Parry Island, Moon River-Twelve Mile Bay, Little Lake and Head Lake-Smudge Lake bodies.

The Central Metasedimentary Belt Boundary Zone is roughly northeast trending, and separates the Central Gneiss Belt from the Central Metasedimentary Belt. The Central Metasedimentary Belt is subdivided into northeast trending terranes, from west to east, these are the Bancroft, Elzevir, Sharbot Lake and Frontenac terranes. It is this area of the province that many of the syenite and nepheline-bearing rocks occur.

The Percy Lake Anorthosite is situated within the Central Metasedimentary Belt Boundary Zone. The Farquhar Lake Complex is situated south of the Central Metasedimentary Belt Boundary Zone in the Bancroft Terrane. Bancroft Terrane syenites are located in the Gooderham Syenite Belt, Tory Hill Syenite Belt, Bancroft Nepheline Syenite Belt, the Wolfe Nepheline Syenite Belt and as several less distinctive bodies at the northeast end of the terrane, referred to here as the Renfrew County Syenites.

The Elzevir Terrane hosts the Blue Mountain, Gawley Creek, Mount Moriah and Skootamatta Syenites in the south and the Mount St. Patrick and Burns Lake Syenites near the northeast terrane boundary. The Elbow Lake Anorthosite is situated in the northeastern part of the Elzevir Terrane.

The Wilkinson Anorthosite is situated near the southeastern margin of the Sharbot Lake Terrane. There are no syenite occurrences studied from the Sharbot Lake Terrane.

There are no known anorthosite or syenite occurrences studied from the Frontenac Terrane.

Map 1 (after Easton 1991) shows the positions of the major geological subdivisions of Ontario.

Syenites, Nepheline Syenites and Nepheline Gneisses

Syenites, nepheline syenites and nepheline-bearing gneisses are of interest with respect to industrial mineral uses, since they often contain large proportions of alumina and alkalies ($CaO+Na_2O+K_2O$), especially where nepheline is present.

The types of syenite occurrences throughout Ontario are variable. This study does not encompass all occurrences. Better known occurrences, those which are most accessible and well exposed, or occurrences which have been previously studied as nepheline-syenite sources have received detailed study. For simplicity, these occurrences will be discussed in terms of their geological setting as outlined below.

I. Superior and Southern Provinces:
   - i) Alkalic Complexes
   - ii) Syenite Stocks

II. Grenville Province:

Central Gneiss Belt Occurrences
   - i) Bigwood-Rutter Nepheline Syenites
   - ii) Callander Bay Complex

Central Medisedimentary Belt

A. Bancroft Terrane Occurrences
   - i) Gooderham Syenite Belt
   - ii) Tory Hill Syenite Belt
   - iii) Bancroft Nepheline Syenite Belt
   - iv) Wolfe Nepheline Syenite Belt
   - v) Renfrew County Syenites

B. Elzevir Terrane Occurrences
   - i) Blue Mountain Nepheline Syenite
   - ii) Gawley Creek Syenite
   - iii) Mount Moriah Syenite
   - iv) Skootamatta Syenite
   - v) Burns Lake Syenite
   - iv) Mount St. Patrick Syenite

Superior and Southern Province Syenites

An Overview

The Superior and Southern Provinces contain numerous syenite or nepheline syenite occurrences as components of alkalic complexes and small stocks (10 km^2 on average). The Proterozoic Coldwell Complex, the largest of these alkalic complexes in North Amer-

ica, intrudes the Archean Superior Province and is situated along the north shore of Lake Superior. Syenite and nepheline syenite masses occur within the complex. The occurrences of nepheline syenite in the Coldwell Complex have been attributed to extensive fractional crystallization of a basaltic magma (Platt and Mitchell 1982).

The syenite stocks usually occur as silica saturated bodies (recognized by the absence of modal quartz, or nepheline) such as the Otto Stock (Hood Lake Syenite, South Caribou Lake Pluton, Lebel Stock and McElroy Stock). There is a nepheline-bearing syenite associated with the Otto stock, but it is a minor marginal phase. The formation of the nepheline syenite in this case has been attributed to the combined effects of country rock contamination, desilication reactions between country rocks and magma, and metasomatism (Currie 1976).

Nepheline syenite lenses occurring within some bodies are considered to be assimilations of country rock, which have been metasomatically altered to produce nepheline-bearing units. This is the case with the Spanish River Carbonatite Complex (Sage 1987) and possibly the Coldwell Complex (Platt and Mitchell 1982).

Consequently, most nepheline-bearing occurrences do not display the homogeneous, massive-type of nepheline syenite product desirable for industrial mineral applications (see Assessment Files Research Office file 63A.405 regarding mill testing of the Coldwell nepheline syenite) (Sage, personal communication). Nonetheless, alkalic complexes and nepheline syenite associated with syenite stocks such as the Otto Stock unit, can be considered secondary targets worthy of further consideration. Most of these occurrences, and their major rock types, morphologies and possible ages are listed below (after McCrank et al. 1981).

Syenite occurrences of the Superior and Southern Provinces can be classified as follows:

1) Late Archean Suite Syenites representing terminal magmatism of the Superior Province "Kenoran" Orogeny, usually fault associated (Sutcliffe, personal communication)

a) Poohbah Lake Alkalic Complex (Sage, 1988d), mafic nepheline syenite, zoned pluton, Pb-Pb dated at 2667 ±5 Ma (Kwon 1986).

b) Sturgeon Lake Alkalic Complex (Sage, 1988c), nepheline syenite, lenticular form, Pb-Pb dated at 2671 ±31 Ma (Kwon 1986)

c) Herman Lake Alkalic Complex, nepheline syenite, elliptical stock, age probably Archean (Sage, personal communication)

2) Keweenawan Age Syenites, intrusive into the Superior Province. Magmatism is related to Keweenawan rifting at about 1100 Ma and all these bodies are intruded along major faults (Sutcliffe, personal communication).

a) Coldwell Alkalic Complex, gabbro, syenite, nepheline syenite, layered igneous complex, age 1015 Ma.

b) Lackner Lake, nepheline syenite, ijolite, ring complex, Rb-Sr dated at 1092 ±21 Ma (Bell and Blekinsop 1980).

c) Nemegosenda Lake (Sage 1987), carbonatite ijolite, nepheline syenite, ring complex, Rb-Sr dated at 1015 ±63 Ma (Bell and Blekinsop 1980).

d) Otto Stock, syenite, nepheline syenite, zoned stock, age 2680 Ma (Sutcliffe, personal communication).

e) Killala Lake Alkalic Complex (Sage 1988), gabbro, syenite, nepheline syenite, zoned pluton, age 1050 ±35 Ma (Bell and Blekinsop (1980).

3) A third suite of syenites, about 1.8 Ga old, occur at the northern end of the Kapuskasing Structure (Sutcliffe, personal communication) but are less well known.

A series of studies on alkalic and carbonatite complexes have been published by Sage (1988a-d). These studies provide detailed descriptions of most of these occurrences.

Detailed descriptions for these syenite occurrences have not been compiled, since secondary targets do not warrant further consideration under the constraints of this report.

Grenville Province Syenites

Central Gneiss Belt

Two nepheline syenite occurrences, the Callander Bay Complex and the Bigwood-Rutter Syenite occur in the Central Gneiss Belt. These two occurrences are quite different in character.

The Middle Proterozoic (Easton, personal communication) Bigwood-Rutter Syenite is part of the west end of the Central Gneiss Belt, situated north of the northeast corner of Georgian Bay. The body forms the west limb of the tightly folded syenite gneisses of the French River Alkalic Complex.

The Early Paleozoic (Easton, personal communication), Callander Bay Carbonatite Complex intrudes the gneiss belt. It is situated near the east end of the Central Gneiss Belt, on Callander Bay on Lake Nipissing. The nepheline syenite forms a small arcuate unit which partially encircles the Callander Bay Carbonatite Complex. Numerous dikes of lamprophyre, potassi-

um trachyte and carbonatite, typical of carbonatite complexes, are associated with this occurrence.

Bigwood-Rutter Nepheline Syenite Gneiss

The Bigwood-Rutter (Figure 10) occurrence is part of an elongate body of syenite gneiss which extends north from Allanite Bay on the Pickerel River, and across the French River in Bigwood Township, 65 km south of Sudbury. The occurrence is accessible by secondary roads, south from Highway 69, east of French River. The north end of the body is accessible from Highway 64, south of Rutter. The areal extent of the nepheline units is approximately 4 km^2.

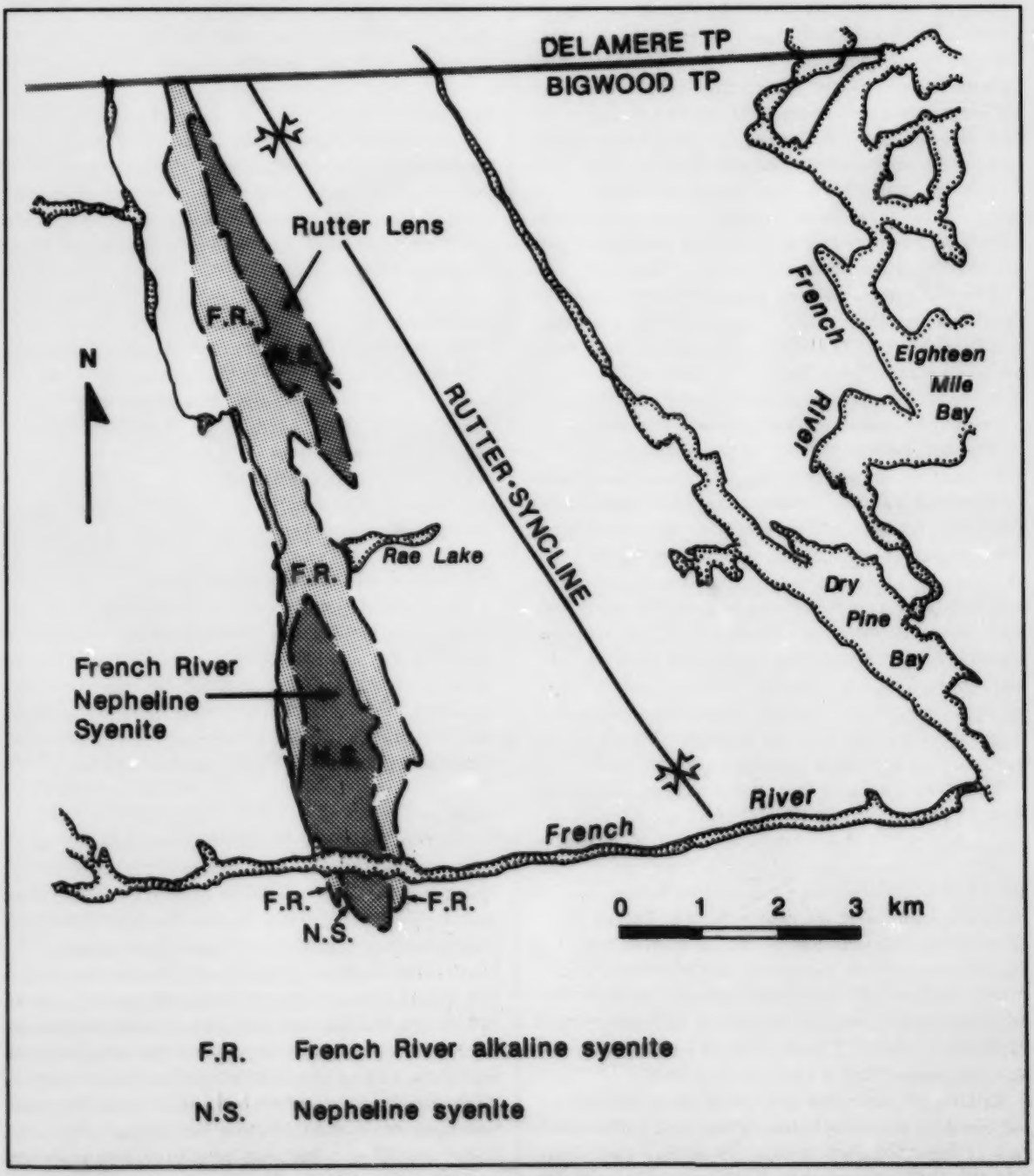


Figure 10. Bigwood — Rutter Nepheline Syenite Gneiss.

Geology

The Bigwood-Rutter occurrence lies in the westernmost part of the Central Gneiss Belt and is probably Middle Proterozoic in age (Easton, personal communication). Hewitt (1960) describes the geology of this occurrence. The north trending units are lensoid masses, comprising most of the west limb of the Rutter Syncline. Two distinct bodies of nepheline syenite gneiss, a north and a south lens, are enclosed by a pink alkaline syenite known as the French River Alkaline Syenite (Hewitt 1960). The alkaline syenite unit is 11 km long, with a maximum width of 0.8 km. The rocks have a pronounced foliation and gneissosity which trend north-northeasterly and dip variably to the east.

The two nepheline syenite lenses are petrographically similar except that the major mafic component differs between the two bodies, with hastingsite predominating in the north and biotite in the south.

The north lens, referred to as the Rutter nepheline syenite is approximately 5.5 km long with an average width of 0.8 km. Texturally, the rock is a medium grained, granoblastic gneiss in which mineral proportions are inconsistent across layering. The layering is defined by concentrations of mafic minerals.

The mineralogy consists of plagioclase (albite in composition), pink nepheline, microcline and hastingsite with accessory biotite, aegerine-augite, and magnetite. Allanite, apatite, carbonate and zircon occur less regularly. Mafic content varies from 5 to 30% but averages 10% mafic minerals. Nepheline ranges from 5 to 50% but averages between 20 and 30% and is pink when fresh. Alteration of nepheline to fibrous zeolite is common where microperthite is abundant and hydrothermal fluids from the adjacent alkaline syenite have invaded the nepheline syenite. Alteration of nepheline is particularly common at the margins where there has been extensive potassic alteration (Hewitt 1960).

The more southerly lens, referred to as the French River Nepheline Syenite (Hewitt 1960) is 5 km long and averages a width of 0.1 km. The nepheline syenite is a medium to coarse grained granoblastic gneiss, consisting of white nepheline, plagioclase (albite, An_{4-9}), and microcline with accessory biotite. Potash alteration at the margins has produced antiperthite and fibrous zeolite from microcline and nepheline respectively. Accessory minerals include hastingsite, aegerine-augite, magnetite, titanite, zircon, apatite, carbonates, sodalite, cancrinite and rarely graphite and corundum (Currie 1976; Hewitt 1960).

Patches of nepheline pegmatite occur throughout the southern lens. Nepheline, albite, and coarse crystals of blue sodalite, yellow to orange cancrinite (Hewitt 1960) and molybdenite (Currie 1976) occur in these pegmatite patches. Layering is defined by concentrations of biotite and nepheline. Nepheline constitutes only 10 to 20% of the body.

Economic Aspects

The economic potential of these nepheline syenites has not been studied although Currie (1976) remarks that there is a persistent association of molybdenite, which occurs as giant flexed crystals in the nepheline pegmatite patches.

Exposure

The northern Rutter body is the better exposed of the two nepheline syenites. Map 1960f (Hewitt 1960) indicates that up to 20% of the northern nepheline syenite is exposed whereas in the southern lens only 5 to 10% crops out. This body is best exposed along the shores of the French River.

Geochemistry

Hewitt (1960) (Table 20) lists two analyses of the French River nepheline syenite, two analyses of the Rutter nepheline syenite and two analyses of the associated pink alkaline syenite. The nepheline-bearing samples all contain over 20% Al_2O_3. The total alkali content ($CaO+Na_2O+K_2O$) averages 15.3% for the nepheline-bearing samples and is slightly lower in the alkaline syenite averaging 13.2%.

Callander Bay Nepheline Syenite

The Callander Bay Complex is situated in a small round crater (Figure 11), much of which lies beneath Callander Bay on Lake Nipissing. A north trending arc of nepheline syenite is exposed over an area of approximately 4.5 km^2, along the northeast shore of Callander Bay. Access is provided along secondary roads from Highway 11 and through the town of Callander.

Geology

The Callandar Bay Complex forms a circular body, Early Proterozoic in age (Currie and Ferguson 1971), which intrudes gneisses of the eastern Central Gneiss Belt. Drilling in Callander Bay has revealed a complex of alternating fenitic syenite and carbonatite surrounded by nepheline syenite at the eastern margin (Currie and Ferguson 1971). Currie and Ferguson (1971) propose that the nepheline syenite formed by separation from an initially nephelinitic magma, during a late stage of immiscibility. The fenite aureole, potassium trachyte lamprophyre dikes and carbonatite dikes present in the Callander Bay Complex are typically associated carbonatite complexes. The nepheline syenite is described in detail by Ferguson and Currie

Table 20
Chemistry of the Bigwood-Rutter Syenite

	1	2	3	4	5	6
SiO_2	58.27	59.03	56.35	55.90	65.52	65.96
TiO_2	0.63	0.03	0.16	0.05	0.04	0.03
Al_2O_3	20.35	21.81	20.31	22.12	18.61	18.92
Fe_2O_3	1.33	2.34	2.66	0.96	1.00	0.48
FeO	2.92	1.34	4.09	4.33	1.17	0.53
MnO	0.22	0.03	0.18	0.14	0.03	0.03
MgO	0.08	0.06	0.11	0.37	0.10	0.08
CaO	0.21	0.53	1.69	0.44	0.45	0.23
K_2O	3.88	4.36	4.86	6.42	5.13	5.90
Na_2O	11.68	10.78	8.31	8.35	7.58	7.17
H_2O	0.31	0.15	0.69	0.57	0.24	0.15
P_2O_5	0.07	0.02	0.04		0.01	0.04
CO_2	0.32		0.67	0.67	0.02	0.16
$CaO+Na_2O+K_2O$	15.77	15.67	154.86	15.21	13.17	13.30
TOTAL	100.27	100.48	100.02	100.32	99.91	99.68

1,2. Hastingsite-aegerine-nepheline syenite gneiss from the northern Rutter lens.
3,4. Biotite-nepheline syenite gneiss from the southern, French River lens.
5,6. Syenite enclosing nepheline-bearing rocks along the French River.

(after Hewitt 1960)

(1972). Mesocratic nepheline syenite, leucocratic nepheline syenite and as nepheline syenite dikes are present (Currie 1976).

The mesocratic nepheline syenite is grey in colour and occurs around the northeast end of the body. These rocks are heterogeneous and coarse grained, characterized by mafic aggregates which are usually 0.5 to 1.0 cm in diameter but can reach 8.0 cm diameter. Modal analyses of two samples from this unit show aegerine at 26.1% and 34.3%, nepheline at 45.1% and 19.2%, K-feldspar/perthite at 20.6% and 2.8%, biotite at 3.5% and 38.6%, sphene at 3.6% and 3.8%. Both samples contain accessory apatite (1% or less). Evidently the mineral proportions are highly variable throughout this mesocratic nepheline syenite.

The leucocratic nepheline syenite surrounds the mesocratic unit to the east, and extends south as far as Burford Point. This rock is pink, coarse-grained and locally trachytic in texture. The mineralogy of this unit is somewhat less variable with K-feldspar/perthite comprising over 50% of the rock in all four modal analyses listed. Nepheline content ranges from 18.2% to 43.2%, aegerine is present from 0% to 8.8% and biotite, magnetite, hematite + sphene and calcite occur in minor amounts.

There are four nepheline syenite dikes, ranging in width from 10 to 20 m, with a maximum length of 1500 m. The dike rocks are composed of homogeneous, coarse grained, markedly trachytoid, leucocratic nepheline syenite.

Pegmatites occur sporadically throughout all the nepheline syenites and mineralogy is variable with localized concentrations of nepheline. Nepheline and feldspar grains reach 4 cm in length. Aegerine veinlets (1 to 4 mm wide) also occur throughout the nepheline syenites.

Lamprophyre dikes cross cut all the rocks of the Callander Bay Complex, but are more commonly found in the mesocratic unit than in the leucocratic nepheline syenite.

Economic Aspects

Hewitt (1960) reports that the nepheline potential of the Callander Bay nepheline syenite has been studied, but the rocks contain too much Fe to be of commercial value.

Exposure

Outcrop is discontinuous from the Old Mill site on the north shore of Callander Bay south to Burford

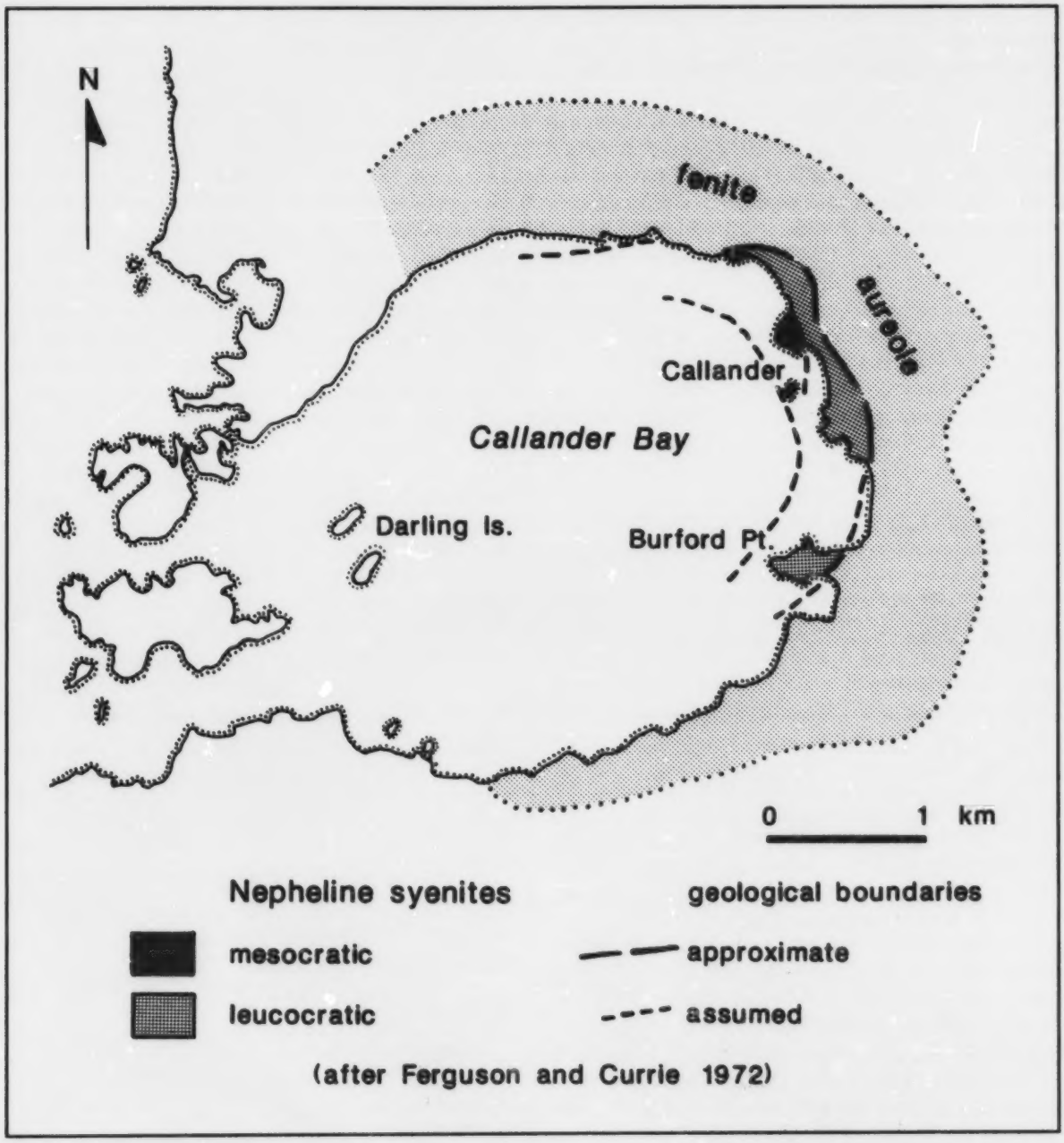


Figure 11. Callander Bay Complex.

Point on the east side of the bay. The nepheline syenite dikes are exposed semicontinuously along their lengths.

Geochemistry

Table 21 (Ferguson and Currie 1972) shows seven analyses of the Callander Bay nepheline syenites. There are four analyses of the leucocratic nepheline syenite, two analyses of the mesocratic nepheline syenite and one analysis of a nepheline syenite dike. The leucocratic nepheline syenite is more homogeneous, with a lower total mafic content and is therefore the most prospective for Al_2O_3 and $CaO+Na_2O+K_2O$. The alumina content of the leucocratic nepheline syenite averages 21.7% and total alkali content averages 14.25%. The total alkali content is slightly higher for

Table 21
Chemistry of the Callander Bay Complex

	1	2	3	4	5	6	7
SiO_2	53.00	58.68	55.34	53.70	48.20	50.87	50.76
TiO_2	0.46	0.37	0.47	0.45	1.02	1.21	1.34
Al_2O_3	23.50	19.80	21.04	22.60	20.20	18.92	20.80
Fe_2O_3	2.10	1.84	2.26	1.90	3.50	3.55	1.05
FeO	1.80	0.14	1.40	1.60	2.70	2.50	4.20
MnO	0.15	0.11	0.08	0.15	0.29	0.22	0.11
MgO	1.00	0.24	1.90	2.30	4.30	2.05	2.93
CaO	1.00	0.74	1.36	1.70	4.40	3.81	3.18
Na_2O	4.13	5.07	2.16	3.47	3.08	6.81	3.49
K_2O	8.73	9.47	9.86	9.25	8.20	7.88	7.52
P_2O_5		0.14	0.08	0.06	0.28	0.25	0.33
H_2O	2.80	0.90	2.80	3.00	3.10	0.80	4.60
CO_2	0.20	0.60	0.80	0.80	1.00	0.40	
$CaO+Na_2O+K_2O$	13.86	15.28	13.38	14.42	15.68	18.50	14.19
TOTAL	98.87	99.36	99.94	100.98	100.27	99.27	100.31
ppm							
RB	205	270	270	225	160	140	
SR	1400	1900	1200	1500	3000	2100	1300
BA	1100	920	1000	1200	2400	2500	3800
ZR	440	250	490	630	1600	630	1200
NB	50	140	250	200	225	220	130

1, 2, 3, 4. Leucocratic nepheline syenite.
5, 6. Mesocratic nepheline syenite.
7. Nepheline syenite dike.

(Ferguson and Currie 1972)

the mesocratic samples, at 15.68% and 18.5%, however the alumina content is slightly lower at 20.2% and 18.92%. Iron content is 2 to 3% higher in the mesocratic rocks.

The Central Metasedimentary Belt Syenites

The Bancroft Terrane

Syenites and associated nepheline-bearing rocks occur as a 300 km long, semicontinuous band, extending the entire length of the Bancroft Terrane. For the most part, the syenitic rocks comprise of a series of narrow, linear, semicontinuous belts. At the northeast end of the terrane, however, the occurrence of syenitic rocks is more widespread, extending 20 km or more laterally. Individual bodies range from small sill-like occurrences of probable igneous origin in the southwest, to those in the northeast which are larger, more deformed, amorphous bodies (Lumbers, personal communication, 1989), likely the result of several processes (e.g., metamorphism, metasomatism, injection of magmas, anatexis, etc.).

A multitude of names have been given to the various mineral occurrences associated with nepheline-bearing and syenitic rocks in the Bancroft Terrane. For the sake of simplicity, these occurrences will be grouped as follows: 1) Gooderham Syenite Belt, 2) Tory Hill Syenite Belt, 3) Bancroft Nepheline Syenite Belt, 4) Wolfe Nepheline Syenite Belt, and 5) Renfrew County (refer to Map 3 for locations).

The Gooderham Belt grades from small (scale of hundreds of metres), discrete, sill-like bodies in the south to more continuous, lenticular bodies to the northeast. The sill-like bodies range from leucocratic to melanocratic monzodiorite (Easton 1987a) whereas occurrences further to the northeast are long narrow

lenses of syenite, which locally contain nepheline-gneiss. The belt extends 15 km to the northeast from Irondale, gradually becoming more continuous, extending 15 km northeast from Irondale and is no wider than 2 km.

The Tory Hill belt is more continuous than the Gooderham Belt, and wider (up to 5 km), consisting of elongate, curvilinear lenses similar to those of the Gooderham Belt. The belt extends 40 km along a northeast trend. The west half of the belt lies immediately south and parallel to the Gooderham Syenite belt, extending northeast from Irondale to Cardiff. The east end of this belt is exposed in a concentric band centred over the Cardiff Dome.

The Bancroft Syenite Belt reaches widths of 5 to 8 km and extends roughly 40 km, northeasterly from southeastern Cardiff Township. The belt has a sigmoidal shape, with east trending extremities and a central north-northeasterly trending section. The Bancroft Nepheline Syenite Belt dies out to the east around Conroy Marsh in Carlow Township.

The much smaller Wolfe Nepheline Syenite Belt, lies 25 km due east of where the Bancroft Belt terminates. This belt trends to the east-southeast and is continuous over a 10 km length with a width of only a few hundred metres. Two small, unnamed occurrences of nepheline syenite are known to occur, east of the Wolfe Nepheline Syenite Belt. The first, 2 km northeast of where the Wolfe Nepheline Syenite Belt terminates, is augen shaped, 1 km long and no more than 300 m wide. The second, is a much smaller nepheline-syenite occurrence, (less than 500 m long and 50 m wide) which lies within carbonate metasediments, and is closely related to a larger syenite body of the Northeastern Syenite occurrences. It is not known whether these two small occurrences of nepheline syenite are related to the Wolfe Nepheline Syenite Belt.

The Northeastern Syenites differ significantly from the other belt-type syenite occurrences in the Bancroft Terrane. They cover a much larger area and occur as irregularly shaped masses of a mixed assemblage of syenite plus metasediments, granites and gabbros.

The nepheline potential of the Bancroft Terrane alkalic belts has been scrutinized for over 50 years (Hewitt 1960). To date, there are no nepheline producers in this terrane.Terminology used in describing these alkalic rocks is described in the introduction to syenite occurrences.

Gooderham Syenite Belt

This belt consists of a series of northeasterly trending lenses strung out over a length of 40 km. The belt varies in width from hundreds of metres to a few kilometres, where continuous. Nepheline-bearing rocks occur as lensoid bodies, closely associated with the syenite. Nepheline gneisses occur in Somerville, Galway, Snowdon, Glamorgan and Monmouth townships. Exposures are easily accessible on foot, via Highways 121, 503 and 507 (Figure 12) and county roads.

Geology

The Gooderham Syenite Belt is enclosed mainly by marbles stretching half the length of the Bancroft Terrane in the Grenville Province. The southwest end of the belt consists of four distinct units. From the southeast boundary of Glamorgan Township the belt becomes more continuous and the well known nepheline gneisses of Glamorgan and Monmouth townships (Hewitt 1960; Currie 1976) occur in this part of the belt.

Alumina and alkali proportions are not necessarily high throughout the belt, but leucocratic and nepheline-bearing units are known to contain combined alumina and alkali contents greater than 35%.

The discrete bodies in the south end of the belt are typically medium- to coarse-grained rocks, in sharp contact with the surrounding marbles, and locally preserving primary igneous layering. Igneous origins have been suggested for these rocks (Easton 1987a).

The most southerly occurrence of the belt (labelled "A" on Figure 12) lies at the northeast boundary of Somerville Township. The body is sill-like, (Easton 1987a), elongate from north to south and dips 15° to the southeast (Easton 1987a). It covers an area approximately 500 m by 150 to 200 (75 000 to 100 000 m^2). The rock is a leucocratic, monzodiorite gneiss (Easton 1987a). The mineralogy is: 65% plagioclase of oligoclase to andesine composition, 25% microcline plus orthoclase, 2 to 5% mafic (hornblende altered to chlorite) and 1 to 3% magnetite (Easton 1987a). Nepheline may also be present although none has been observed (Easton 1987a).

The next body to the north (labelled "B" on Figure 12) is 200 to 250 m thick and 500 m long with a smaller northern extension separated from the main body by overburden. The rock is a leucocratic nepheline-monzodiorite (Easton 1987a). The mineralogy consists of predominantly coarse-grained, granular feldspar, with local concentrations of magnetite. Modes are: 75% andesine and oligoclase plagioclase, 15% microcline, plus orthoclase, 5 to 10% opaques, 2 to 5% chloritized mafics (probably biotite and hornblende) (Easton 1987a). Accessory calcite crystals and 1 to 2% nepheline are also present (Easton 1987a).

The third and largest of these discrete bodies

(labelled "C" on Figure 12) is much more mafic. The body is 250 to 300 m thick and 500 m long. The bulk composition is hornblende-pyroxene-monzodiorite and layering gives the body a very heterogenous appearance (Easton 1987a). The increased mafic content of the body makes it a less attractive target for alumina and alkali content.

Two very small bodies (approximately 500 m by 100 m) occur around 1 km to the northeast of "C". The rocks of this locality are described by Easton (1987a) as friable, white to pink weathering, monzodiorites with local concentrations up to 15% magnetite and possibly containing altered nepheline.

The Gooderham Syenite Belt differs in character northward from these small, discrete bodies. This part of the belt is a long (approximately 15 km), narrow (0.3 to 1.5 km) semicontinuous unit, containing nepheline gneiss units within syenite. The nepheline-bearing rocks occur as lenticles within typically gneissic syenites which are enclosed for the most part by marbles. The intrusive or igneous nature of these occurrences becomes much less evident towards the northeast end of the belt (Easton, personal communication).

Individual nepheline-bearing lenses are indicated on Figure 12 (after Hewitt 1960; Currie 1976) and details of mineralogy are given by Hewitt (1960). The gneiss generally dips to the south (35° to 50°), following the contact with the country rocks.

The mineralogy of these occurrences is highly variable. Nepheline content is generally low, occurring as sparsely disseminated grains and occasionally as unevenly distributed clusters (up to 2.5 cm by 8.0 cm). Albite plagioclase is ubiquitous with biotite and hornblende present in varying proportions. Microcline is common, and scapolite, calcic pyroxene (hedenbergite and hastingsite), garnet, magnetite and graphite are also present in lesser amounts. Scattered corundum and magnetite crystals occur throughout these nepheline gneisses. Unlike the other belts of the Bancroft Terrane, the Gooderham Belt does not contain nepheline pegmatites (Hewitt 1960).

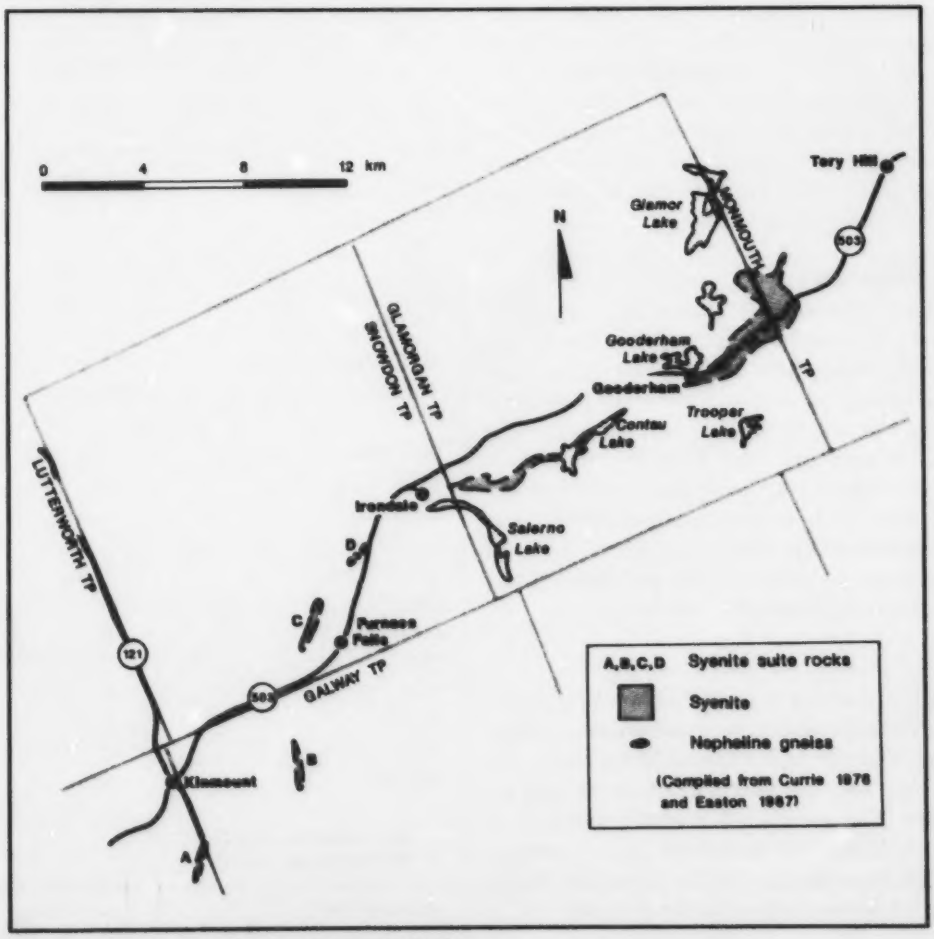


Figure 12. Gooderham Syenite Belt.

Economic Aspects

Except for scattered magnetite and corundum occurrences, there are no mineral occurrences in the Gooderham Syenite Belt. At the time of Hewitt's report (1960), the nepheline gneisses were not considered commercially valuable due to their small size, and widely variable nepheline content. Assessment file records indicate that there has not been any recent mining activity in the rocks of this belt (Assessment File Research Office, Ontario Geological Survey, Toronto, Ontario).

Exposure

The rocks described are well exposed. However, it is possible that several of the units (particularly those to the south) are continuous but are covered by overburden. Exposures disappear under swamp just east of Gooderham.

Geochemistry

There are analyses for unit B and unit C (Table 22), both monzodiorites from the discrete bodies to the south of the main part of the belt. Al_2O_3 is 19.5 and 17.3 weight % respectively, and the total alkali contents are 14.24 and 14.8% respectively (Easton 1987a). The sample from unit B is nepheline-bearing. It is likely that these rocks are chemically very similar to the nepheline gneisses of the Tory Hill and Bancroft Belts. Refer to Table 23 and Table 24.

Tory Hill Syenite Belt

The Tory Hill Syenite Belt (Figure 13) is a narrow linear unit which trends northeasterly for over 45 km. It extends from Galway Township where it is less than 500 m wide, crossing the northwest corner of Cavendish Township, and widening (3 to 5 km) as it passes through Glamorgan, Monmouth and Cardiff townships. Nepheline occurrences are closely associated with the syenite belt particularly in Monmouth Township. The belt is accessible from Irondale, off Highway 503 and county roads between Furnace Falls and Gooderham, and on foot from Highways 121 and 507.

Geology

The Tory Hill Syenite (Figure 13) is a long semi-continuous belt adjacent to the northwest boundary of the Bancroft Terrane in the Grenville Province. The south end of the belt is a very narrow (50 to 100 m) lense of syenite. This syenite unit gradually widens into Glamorgan and Monmouth townships where it ranges from 3 to 5 km in width. It is in this wider part of the belt that nepheline-bearing rocks are common.

The syenite is a medium-grained, buff coloured, hornblende syenite gneiss (Currie 1976). Nepheline-biotite-gneisses occur as lenticles either within or adjacent to the syenite. Igneous textures have been noted at the northeast end of the belt which is in contact with gabbroic rocks (Monmouth Township line) (Currie 1976). Albite plagioclase laths and cubic nepheline occur in a matrix of calcic pyroxenes (hedenbergite, hastingsite) and biotite. Nepheline at this locality is more sodic than in other parts of the belt and acicular pyroxene inclusions are reported in the nepheline (Hewitt 1960). Beneficiation of an alumina/alkali concentrate would be complicated by these

Table 22
Chemistry of the Gooderham Syenite Belt

	1	2
SiO_2	54.50	52.30
TiO_2	0.19	0.15
Al_2O_3	17.30	19.50
Fe_2O_3	10.10	9.64
FeO		
MnO	0.14	0.22
MgO	0.18	0.16
CaO	3.78	4.19
K_2O	5.84	1.43
Na_2O	5.18	8.62
P_2O_5	0.05	0.06
CO_2	2.14	2.14
LOI	0.09	2.00
$CaO+Na_2O+K_2O$	14.80	14.24
TOTAL	98.20	98.30
NORMS		
QTZ	0	0
ORTHO	35.8	8.8
ALB	27.9	44.4
ANOR	7	10.8
DIOP	11	9.8
HYPER	0	0
MAG	2.5	2.5
ILM	0.4	0.3
OLIV	5.8	5.9
APA	0	0
NEPH	9.5	17.3

1. Monzodiorite, Unit C.
2. Monzodiorite, Unit B.

(Easton 1987)

inclusions in the nepheline. More perthitic (microperthite) with minor fayalitic olivine facies occur further still to the northeast. This rock grades into white biotite nepheline gneiss, which is typical of the belt, further to the northeast (Currie 1976). Nepheline content decreases steadily towards the northeast (Currie 1976).

Economic Aspects

Uranium prospects have been discovered near these alkalic rocks and it is possible that U mineralization is related to the nepheline syenites (Currie 1976). Molybdenum occurrences are common in the syenite pegmatites in this area and may be related to the Denna Lake Structural Complex to the north which hosts the same disseminated flakes of molybdenite.

Exposure

Reports of trenching and the occurrence of pits in the nepheline gneisses (Hewitt 1960) would suggest that exposure is very good.

Geochemistry

Chemical analyses are available (Tilley and Gittins 1961) for several of the nepheline-gneiss lenses of the Tory Hill Belt (Table 23). Alumina content varies from 18.07% for a nepheline-rich gabbro to 26.42% for a nepheline-oligoclase-biotite gneiss. Alkali content appears to be consistently high with values over 16%. Easton (1987) also provides an analysis of a syenite from the Tory Hill Belt with Al_2O_3 at 16.6% and total alkali content at 15.76% (Table 23). This sample is not nepheline bearing, perhaps accounting for the lower Al_2O_3 value.

Bancroft Syenite Belt

The Bancroft Syenite Belt is the largest of the Ban-

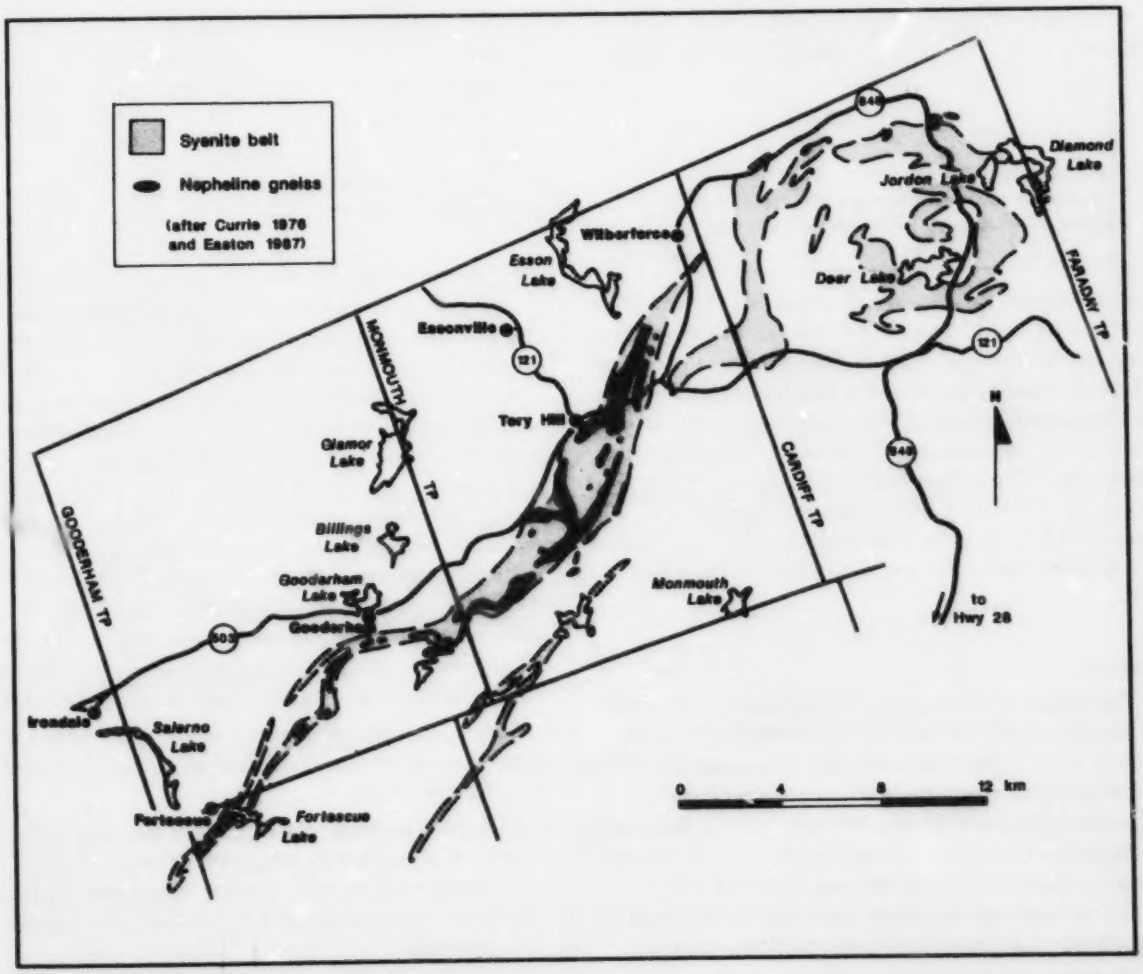


Figure 13. Tory Hill Syenite Belt.

Table 23
Chemistry of the Tory Hill Syenite Belt

	1		2	3
SiO_2	55.50	SiO_2	52.23	51.72
TiO_2	0.80	Al_2O_3	19.50	19.38
Al_2O_3	16.60	Fe_2O_3	4.44	4.22
Fe_2O_3	6.51	FeO	5.78	6.70
FeO		MnO	0.21	0.17
MnO	0.11	TiO_2	0.42	0.45
MgO	0.79	MgO	0.20	3.45
CaO	5.42	CaO	3.52	7.06
K_2O	4.71	Na_2O	7.59	5.17
Na_2O	5.53	K_2O	5.41	0.75
P_2O_5	0.14	H_2O+	0.57	0.06
CO_2	1.50	H_2O-	0.03	0.16
LOI	2.22	P_2O_5	0.14	0.03
$CaO+Na_2O+K_2O$	15.66	CO_2	0.12	0.32
TOTAL	98.60	C	0.19	
		$CaO+Na_2O+K_2O$	16.52	15.68
		TOTAL	100.35	99.64

1. Syenite (Easton 1987).
2. Coarse-grained nepheline syenite, lot 4, con. IV, Monmouth Township. (Tilley and Gittins 1961))
3. Fine-grained nepheline syenite, lot 4, con. IV, Monmouth Township. (Tilley and Gittins 1961).

croft Terrane syenite belts, extending 50 km from southeast Cardiff Township, through Faraday, Dungannon, Monteagle, Carlow and Raglan townships. The belt pinches out at either end but widens to 8 km in Dungannon Township. This belt (Figure 14) includes the East Road, Bronson Landing, York River Belt, Monteagle Corundum Belt and Carlow-Monteagle occurrences (Currie 1976; Hewitt 1960; Hewitt and James 1956). Access is available along any of the roads from Bancroft, which lies in the centre of the belt.

Geology

The Bancroft Syenite Belt is the central syenite belt of the Bancroft Terrane in the Grenville Province. Hewitt (1954; 1960) provides detailed descriptions of the rock types, mineralogy, and textures of these rocks. The most prominent feature of these rocks is their heterogeneity. The rocks are strongly banded, with wide compositional variations across layering and along strike of layering. All these rocks are overprinted by strong regional metamorphism and deformation.

Syenites, granites, metasediments and nepheline-bearing rocks are all interlayered. The nepheline-gneisses are interbanded with metasediments, syenites and granites which form lenses in predominantly syenitic rocks. The mineralogy of all these rocks is widely varied. The syenite invades the nepheline gneiss and varies in composition from oligoclase-andesine gneiss to yellow brown hornblende syenite. Granite and granite pegmatite also occur throughout the nepheline-gneisses. The major constituents of the nepheline-bearing rocks are: nepheline, oligoclase plagioclase, scapolite, muscovite, biotite, hornblende and magnetite. Mafic minerals constitute 20 to 30% of the rocks (Currie 1976). Accessory minerals include: garnet, carbonate, titanite, zircon, tourmaline, vesuvianite, fluorite, corundum, pyroxene, microcline and perthite.

Some general statements can be made about the mineral associations in the nepheline-gneisses of the belt (Hewitt 1954).

a) Nepheline-plagioclase gneiss is the most common of nepheline-plagioclase, -hornblende, -hornblende-garnet, -biotite, -oligoclase-andesine, -scapolite, and nepheline-corundum gneisses.

b) Calcic plagioclase predominates (i.e., andesine) when scapolite is present.

c) Scapolite is often most abundant in biotite-bearing gneisses.
d) Corundum-bearing alkaline syenites occur in close association with the nepheline gneisses and corundum is widespread throughout the gneisses.
e) Garnet-bearing facies are prevalent in the Dungannon Township occurrences and are uncommon in the rest of the belt.
f) Nepheline and scapolite are commonly associated with each other in feldspar-corundum and ferromagnesium gneisses (Hewitt 1960).

The textures of these rocks typically form an equigranular, granoblastic mosaic. Granoblastic and poikiloblastic textures occur locally with muscovite halos around corundum.

Nepheline pegmatites crosscut the adjacent gabbro and the nepheline gneiss units. Nepheline pegmatite also occurs as blocks in crystalline limestone breccia at the edge of York River in Carlow Township.

Economic Aspects

The Craigmont Mine at the northeast end of the belt in Raglan Township produced corundum and many other small corundum deposits are known in the belt. None of these occurrences is considered economically significant (Currie 1976; Hewitt 1960).

Geochemistry

The alkalic rocks of Carlow and Monteagle townships are extremely MgO and FeO depleted whereas the high corundum content is reflected by high Al_2O_3 (Currie 1976). Six analyses of samples from this belt are listed (Table 24, after Hewitt 1960). Al_2O_3 content

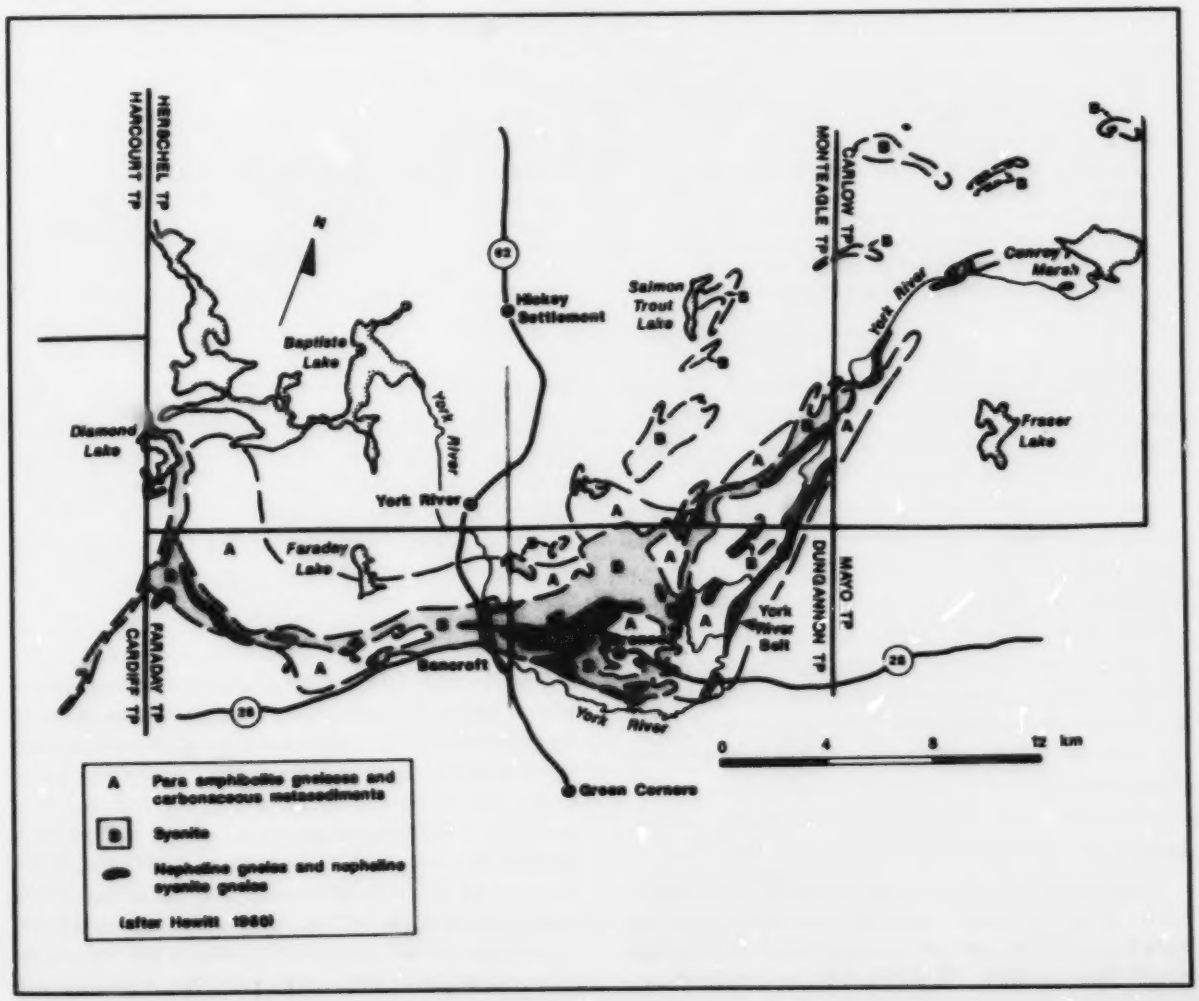


Figure 14. Bancroft Nepheline Syenite Belt.

Table 24
Chemistry of the Bancroft Nepheline Syenite Belt

	1	2	3	4	5	6	7	8	9
SiO_2	49.38	55.45	45.90	64.37	52.29	57.00	45.22	41.73	39.30
TiO_2	tr	0.30	0.07	0.15	0.21	0.14	0.96	0.29	1.96
Al_2O_3	30.54	26.10	29.79	19.41	25.67	24.91	14.07	27.48	13.03
Fe_2O_3	0.40	0.81	1.82	1.10	2.35	3.47	4.02	1.84	6.51
FeO	0.06	0.49	1.44	0.80	1.87	1.26	12.49	4.52	12.52
MnO	tr	0.01	0.04	0.01	0.03	0.02	0.70	tr	0.74
MgO	0.19	0.13	0.71	0.06	tr	tr	2.47	1.24	4.86
CaO	1.87	3.65	3.16	0.31	1.28	0.50	17.78	6.78	16.97
K_2O	3.70	1.62	3.26	5.73	3.49	3.00	0.93	3.16	0.97
Na_2O	13.94	9.31	8.26	6.77	11.26	7.90	5.02	11.05	2.01
H_2O	0.50	1.64	3.78	0.40	0.83	1.21	0.23	0.14	0.74
P_2O_5	0.62	0.01	tr	tr	tr	tr	0.77	0.52	0.58
CO_2	tr	0.88	1.62	0.11	0.69	nil	nil	0.93	nil
$CaO+Na_2O$ $+K_2O$	17.83	14.58	14.68	12.81	16.03	11.40	23.73	21.00	19.95
TOTAL	101.20	100.40	99.85	99.22	99.97	99.41	99.66	99.68	99.89

1. Nepheline-muscovite syenite, trace of corundum, Craigmont Mine.
2. Corundum-rich nepheline syenite, Craigmont Mine.
3. Nepheline albite-corundum gneiss, Klondike Cuts.
4. Pink leucosyenite, altered version of above.
5. Nepheline-muscovite-biotite-albite gneiss.
6. Pink leucosyenite, altered version of above.
7. Nepheline-poor gneiss, York River Belt.
8. Nepheline-rich (72 modal %) gneiss, York River Belt.
9. Amphibolite-nepheline gneiss, York River Belt.

(after Hewitt 1960 and Baragar 1953)

is quite high in several of the six samples, and total alkali content ranges from 11.4% to 17.83%. Nepheline-bearing samples analyzed show proportionately higher Na_2O than CaO or K_2O.

Two analyses of samples from the often referred to "York River Belt" in Faraday Township are listed (after Baragar 1953). The nepheline-poor gneiss has notably high CaO at 17.78%, yielding a total alkali content of 23.73% (Al_2O_3 is only 14.07%).

As well, two samples are listed from Adams and Barlow (1910). These samples were collected from the Raglan Township at the far northeast end of the Bancroft belt. Both samples show Al_2O_3 values over 20%, Table 25.

Exposure

Exposure is estimated at approximately 20% (Hewitt 1954). Nepheline gneiss exposures are noted along the York River Valley, and the "northern Carlow corundum range" (Hewitt 1954). Nepheline-bearing units are readily recognized by their pitted surfaces in outcrop. Pits and trenches are common in areas of corundum deposits.

Wolfe Nepheline Syenite Belt

The Wolfe Nepheline Syenite Belt is a small east-trending belt (Figure 15), 7 km long, 200 to 300 m wide, which lies for the most part in Lyndoch Township. The body is crossed by Highway 515 and exposures are easily within walking distance east from the highway and local roads (Currie 1976).

Geology

The Wolfe Nepheline Syenite Belt is the most easterly of the belt type nepheline/syenite occurrences of the Bancroft Terrane. The nepheline gneiss is enclosed by syenite and carbonate metasediments more typical of the northeast end of the Bancroft Terrane. The gneiss consists predominantly of albitic plagioclase, microcline, oligoclase, nepheline and hastingsite (Hewitt 1953). All these minerals occur in widely variable proportions. Corundum, scapolite, hornblende and biotite are also major components but are usually present in lesser amounts. These rocks are characteristically heterogeneous, much the same as the rocks of the Bancroft Belt. Layering of syenitic,

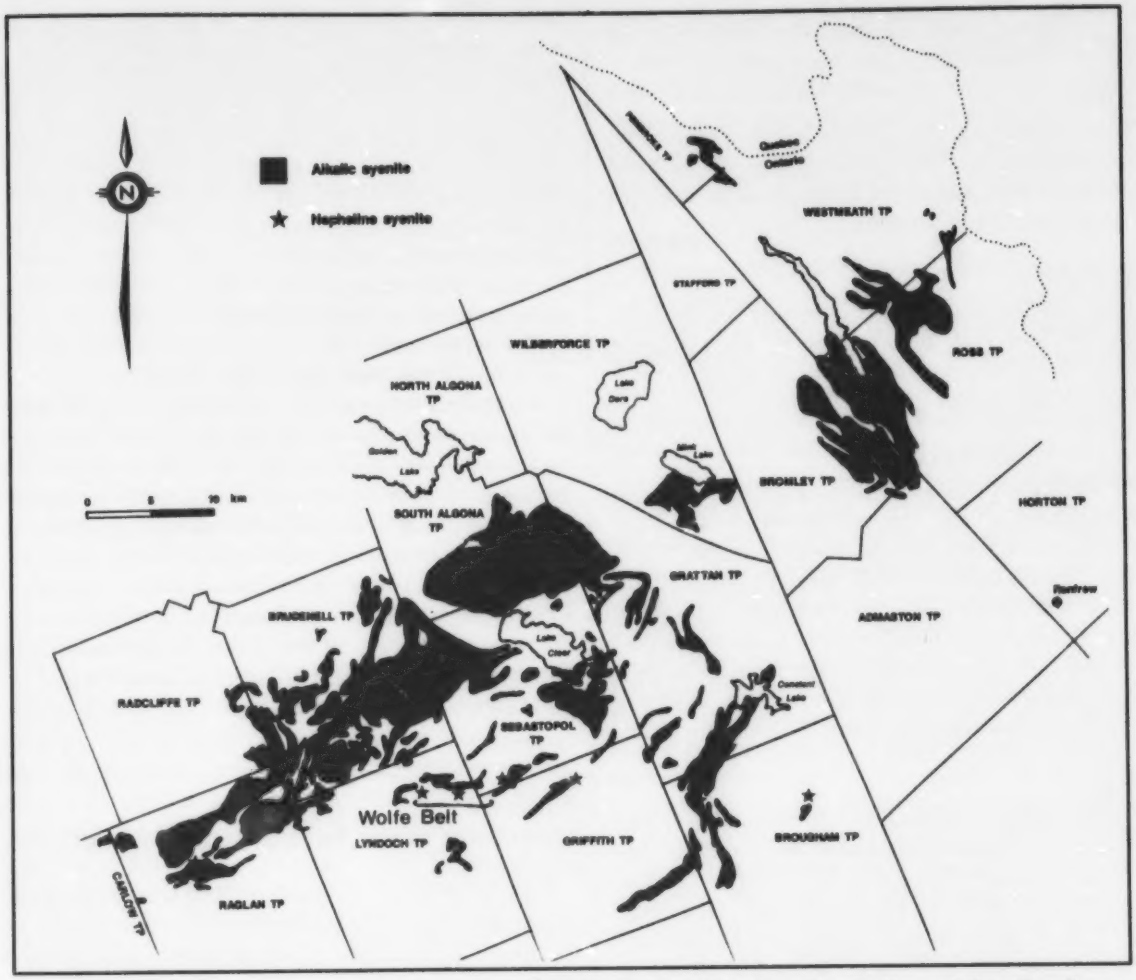


Figure 15. Map Showing Location of the Wolfe Nepheline Syenite Belt and the Renfrew County syenites.

granitic and nepheline-bearing rocks form the pervasively gneissic textures.

The mineralogy and petrography of these nepheline-bearing rocks is described in detail by Hewitt (1954) and Appleyard (1967; 1969). Nepheline, scapolite, pyroxene and albite locally occur in concentrations comprising 40% or more of the rock. Feldspars and nepheline grains are closely spatially related and often intricately intergrown. Oligoclase is veined and replaced by albite, feldspars are replaced by nepheline and nepheline is replaced locally by sodalite. Cancrinite and calcite occur as inclusions in nepheline. The textural relationships between alumina and alkali-rich minerals (feldspars and feldspathoids) appear to be favourable for producing an Al_2O_3 concentrate, except in the few cases where mafic contamination occurs (e.g., pyroxene inclusions in nepheline).

Garnet, aegerine, magnetite, fluorite, vesuvianite, carbonate, titanite, apatite and zircon are present in minor amounts, usually as accessories. Reibeckite occurs only in the central part of the belt (Currie 1976). Biotite rims mafic minerals locally, garnet and scapolite occur as major mineral components in localized patches (Hewitt 1960). Accessory zircon, sphene and fluorite are ubiquitous (Currie 1976).

Nepheline-albite pegmatite with accessory fluorite, apatite, biotite, and zircon occurs at the west end of the belt. Nepheline content is reported as extremely variable and erratic.

Economic Aspects

Shallow pits and trenches are common in pegmatitic patches of the nepheline-gneiss (Hewitt 1961). At the time the belt was studied in detail, nepheline content

was considered too erratic to be of economic value (Hewitt 1961; Satterly 1944).

Exposure

The nepheline-gneisses of the belt form a prominent, 6.5 km long, east-southeast trending ridge, the west end of which has been suggested as the most prospective part of the belt (Hewitt 1960).

Geochemistry

There is no known available chemistry for the rocks of this belt, however, reports of mineralogy suggest possibly high Al_2O_3 and alkali contents (plagioclase + perthite + nepheline).

Renfrew County Syenites

The Renfrew County syenites (Figure 15) extend northeasterly from the easternmost end of the Bancroft Belt, through Raglan, Brudenell, Lyndon, South Algona, Sebastopol, Griffith, Grattan, Brougham, Bromley, Westmeath and Ross townships in Renfrew County. Access is provided to these areas by numerous roads and: Highway 62 north from Bancroft, Highway 41 between Pembroke and Denbigh, Highway 60 between Madawaska and Eganville (Lumbers 1982).

Geology

Reconnaissance mapping by Lumbers (1982) has covered the entire northeast end of the Bancroft Terrane (all of Renfrew County) at a scale of 1:100 000. Syenitic bodies comprise a significant proportion of the rocks (10% or more) in this region. The bodies vary substantially in size and shape. Some are amoeboid in shape with long, tentacle-like, roughly northeast trending extensions and many are elongate, lenticular bodies. Sizes range anywhere from hundreds of metres wide by 1 to 7 km long for narrow slivers, to more rounded bodies covering areas 10 to 50 km^2.

Although the geographic distribution of these syenites is well defined, petrographic details are not available. Lumbers (personal communication) has determined that the syenites are a heterogeneous mixture of rocks, with carbonaceous metasediments, granitic, amphibolitic, gabbroic and tholeiitic material incorporated into the syenite units. The margins of the syenite are diffuse and abundant country rock inclusions are characteristic. These syenites have complex origins whereby metasomatism, anatexis and metamorphism have played a prominent role in their formation. Strong regional deformation is also prevalent and may account at least in part for the disjointed morphology of these bodies.

Nepheline-bearing facies are much less common in the Renfrew County syenites, and are only present in minor amounts as lenses (often hundreds of metres long by tens of metres wide), sporadically distributed across an area 30 to 40 km wide (northwest to southeast) and 80 to 90 km long (southwest to northeast) (Lumbers 1982). Little can be said for the nepheline-bearing rocks of this part of the terrane since they are not well studied. Refer to maps 2459-2462 (Lumbers 1982) for known nepheline occurrences in the northeast area. The formation of nepheline in these rocks has been generally attributed to metasomatism of carbonaceous sediments (Lumbers personal communication; Easton, personal communication).

Nepheline syenite in Sebastopol, Griffith, and Brougham townships are briefly described by Themistocleous (1981). The occurrences in these townships are all gneissic and are closely associated with potassic syenite, marble and amphibolitic rocks. An augen shaped unit, averaging 300 m width, with a length of approximately 800 m occurs just south of Lambert's Lake in Sebastopol Township and has been considered the most prospective of the nepheline gneisses in the Renfrew area (Hewitt 1954; Themistocleous 1981). The other nepheline gneisses have not been studied in detail.

Table 25
Chemistry of the Renfrew County Syenites

	1	2
SiO_2	55.45	48.38
TiO_2	0.30	tr
Al_2O_3	21.65	30.54
Fe_2O_3	0.81	0.40
FeO	0.49	0.06
MnO	0.01	tr
CaO	3.65	1.87
MgO	0.13	0.19
K_2O	1.62	3.70
NA_2O	9.31	13.94
P_2O_5	0.01	tr
CO_2	0.88	0.62
H2O	1.64	0.50
$CaO+Na_2O+K_2O$	14.58	19.51
TOTAL	100.40	100.20

1. "Raglanite", mineralogy: oligoclase, nepheline, corundum, with accessory muscovite, biotite calcite, magnetite and apatite. (Adams and Barlow 1910).
2. "Craigmontite", mineralogy: nepheline 63.18%, oligoclase 29.66%, muscovite 4.39%, calcite 1.42 %, accessory magnetite and biotite (Adams and Barlow 1910).

Economic Aspects

The occurrence referred to above is considered an eastern extension of the Wolfe Nepheline Syenite Belt (Hewitt 1954; Appleyard 1967). It contains 10 to 30% nepheline, 5 to 17% mafic minerals and is the most prospective of the nepheline-bearing rocks in the three townships (Themistocleous 1981).

Exposure

These rocks are generally poorly exposed. Map 2454 (Themistocleous 1981), which covers the Khartum area, including parts of Sebastopol, Griffith, Grattan and Brougham townships shows exposure at less than 5%. The areas which are underlain by carbonate metasediments, with which the syenites and nepheline-bearing rocks are associated, have the lowest topography. Much of the bedrock is obscured by Paleozoic rocks, particularly to the east, toward the Ottawa Graben region.

Geochemistry

Two chemical analyses (Table 25) are provided by Adams and Barlow (1910). Al_2O_3 content is quite high in the corundum-bearing sample. Nepheline-bearing units do not make up a large proportion of the assemblages in the Renfrew region, and have not been analyzed during the course of regional mapping.

Elzevir Terrane Syenites

The alkalic rocks of the Elzevir Terrane typically occur as large (10 to 40 km^2), round plutonic bodies. Nepheline is present only in the Blue Mountain body. The Mount St. Patrick and Burns Lake Syenites occur toward the northeast end of the terrane, bordering rocks of the Bancroft Terrane. A northeast trending group of syenites, the Gawley Creek Syenite in the south, followed by the Mount Moriah and Skootamatta Syenites are situated to the east and northeast of the Blue Mountain Syenite.

The Gawley Creek, Mount Moriah, Skootamatta and Mount St. Patrick Syenites may be part of a approximately 1085 Ma suite of syenite intrusions that stretch from Madoc in Ontario to Mount Laurier in Quebec (Easton, personal communication). The equivalent plutons have recently been studied in detail by Corriveau (personal communication). These bodies are younger than the peak of Grenville metamorphism, having distinct pluton shapes and little affected by Grenville tectonism (Easton, personal communication) unlike the syenites of the Bancroft Terrane. These bodies are therefore attractive targets since they are relatively uniform, massive, coarse grained homogeneous bodies.

Blue Mountain Nepheline Syenite

The Blue Mountain intrusion (Figure 16) is an oval body, covering approximately 12 km^2. It lies between the towns of Blue Mountain and Nephton, in Methuen Township. Access is provided from Highway 28, approximately 55 km north from Peterborough.

Geology

The body lies within lower amphibolite to greenschist facies rocks of the Elzevir Terrane of the Grenville Province. The body has been dated by Rb/Sr whole rock at 1258 ± 41 Ma (Krogh 1964; data adjusted to proper decay constants). The main mass is tear drop shaped, with a length of 4 km (trending northeast) and a width of 2 km (trending east-southeast). A narrow "tail" extends southward from the main mass, for 9.6 km to Stony Lake. The core of the intrusion is centred over the core of a syncline (Hewitt 1960) and Payne (1968) has proposed that the body is actually a tightly folded sill. The country rocks are typically marble and amphibolite, surrounded by granitic rocks.

The Blue Mountain nepheline syenite consists of a hornblende-bearing, nepheline syenite core, surrounded by gneissic, leucocratic, nepheline syenite, which has minor marginal zones of pink syenite (which is not nepheline-bearing).

Payne (1968) has subdivided the body into zones based on the presence of specific minerals, resulting in the following map units: muscovite-, muscovite-magnetite-, biotite-muscovite-, biotite- and hornblende-nepheline syenite and syenite. In general, these units are gradational into each other, with the exception of the hornblende zone which has sharp contacts with the biotite zone. Grain size is transitional from the fine grained muscovite zone through to the coarse grained hornblende zone. Interlocking, inequigranular, anhedral grain textures predominate right through to the biotite zone. Equigranular, rounded grains predominate in the hornblende zone. The presence of perthite and zoned albite varies somewhat across the zones, with an important distinction made in the biotite-muscovite zone where large albite grains contain fine grained inclusions of calcite, microcline and sphene. The presence of these inclusions could affect mineral processing and hence, warrant consideration when evaluating industrial mineral potential.

The modal abundances are not especially variable. Payne (1968) provides modal analyses of 199 samples containing 48.4 to 58.6% albite, 18.2 to 22.7% microcline, 19.7 to 25.5% nepheline, 0.1 to 4.3% biotite, 0.0 to 3.3% muscovite, 0.2 to 1.1% magnetite. Only the hornblende zone contains any hornblende (3%), as well as minor (0.2%) pyroxene (variety

aegerine-augite). Accessory garnet, calcite and corundum are also present.

Analyses of 14 syenite samples (Payne 1968) give the following modal abundances: 64.9% albite, microcline 20.7%, 7.1% muscovite, 5.0% biotite, and less than 1% each of nepheline, magnetite, calcite. The syenite zone (i.e., the pink syenite) occurs sporadically along the margins of the body, and as dikes in the adjacent metasediments (Payne 1968). Payne (1968) details pegmatite occurrences in the intrusion. Peg-

Figure 16. Blue Mountain Nepheline Syenite.

matites of nepheline syenite and pink syenite occur as concordant lenses except in the hornblende zone where they are crosscutting. They are usually less than 3.3 m long and 0.60 m wide. Mineralogy consists of albite, nepheline and microcline, with minor biotite, magnetite and hornblende. Similar pegmatites occur, often as veins, with variable amounts of muscovite, cancrinite, sodalite, tourmaline, and pyrite.

Mafic bodies occur sporadically within the Blue Mountain intrusion, and are interpreted as one or all of: rafted metasedimentary inclusions, metamorphosed mafic dikes, and shear zones along which mafic minerals have concentrated (Hewitt 1960; Payne 1968).

There are zones of alteration where geikielite, zeolite and microcline have replaced nepheline and albite (particularly where the pink syenite is in contact with the nepheline-bearing syenite) (Hewitt 1960).

Economic Aspects

The Blue Mountain nepheline syenite is quarried by Indusmin, a subsidiary of Falconbridge Ltd. In 1988, their production of nepheline syenite and feldspar combined totalled 900 000 tonnes (Gardiner 1989). As well, magnetite is produced from the nepheline syenite at Blue Mountain (Kingston et al. 1988) and is covered in the review of process technologies earlier in this report. The great economic value of the Blue Mountain nepheline syenite is attributed to the low mafic content, uniform composition and grain size (Currie 1976).

Exposure

The Blue Mountain nepheline syenite forms a hill, with relief of 60 to 70 m above the surrounding rocks. A series of 70 m high ridges expose the nepheline syenite between St. Charles and Devils Lakes. Exposure throughout the body is therefore good. As well, the two quarries expose large sections of the body and there has been extensive stripping in the area (Currie 1976).

Geochemistry

Major elements and norms for several samples are given by Hewitt (1960). Ten analyses are listed here in Table 26. Total alkali content is slightly lower in the altered samples, but averages 14.23% for the 10 sam-

Table 26
Chemistry of the Blue Mountain Nepheline Syenite

	1	2	3	4	5	6	7	8	9	10
SiO_2	58.4	58.72	58.69	58.69	59.68	59.8	59.56	58.79	63.32	59.84
TiO_2	0.01	0.01				0.08	0.13	0.03	0.08	
Al_2O_3	24.8	23.07	23.68	22:7	23.48	22.12	24.69	23.77	18.97	23.26
Fe_2O_3	0.75	0.93	0.66	1.31	0.59	1.03	0.44	1.06	2.21	1.43
FeO	0.46	0.91	0.9	0.67	0.37	1.61	1.28	0.81	0.88	0.53
MnO	0.01	0.04	0.02	0.04		0.1	0.04	0.04	0.04	0.05
MgO	0.14	0.03	0.07	0.21		0.01	0.03	0.04	0.01	0.03
CaO	0.59	0.53	0.35	0.56	0.26	4.48	0.43	0.41	1.18	0.66
K_2O	4.34	5.23	5.82	4.61	4.68	1.44	3.89	4.42	5.35	4.75
Na_2O	10.58	10.2	9.57	10.51	9.52	8.72	8.8	10.69	7.28	10.09
H_2O	0.42	0.42	0.31	0.19	0.66	0.46	0.6	0.28	0.35	0.19
P_2O_5	0.01	0.01	0.07	0.01		0.01	0.02	0.02	0.03	0.01
CO_2	0.1	0.14	0.04			0.26	0.19	0.05	0.63	0.13
$CaO+Na_2O+K_2O$	15.41	15.96	15.47	15.68	14.46	14.64	13.12	15.52	13.81	15.51
TOTAL	100.5	100.24	100	99.37	99.49	100.12	100.1	100.41	100.33	99.97

1. White muscovite-nepheline syenite gneiss from one of quarries.
2. Hastingsite-biotite-nepheline syenite gneiss.
3. Biotite-nepheline syenite gneiss.
4. Andradite-nepheline syenite gneiss.
5. Muscovite-biotite-nepheline syenite gneiss.
6. Garnet-hastingsite-nepheline syenite gneiss.
7. Nepheline-corundum-albite-muscovite-biotite gneiss, Stony Lake.
8. Nepheline-biotite-muscovite gneiss, Stony Lake.
9. Syenite gneiss (nepheline-free).
10. Nepheline syenite gneiss from quarry.

(after Hewitt 1960)

ples. Al_2O_3 content ranges from 22.7 to 25.2% for nepheline-gneiss samples.

Gawley Creek Syenite

The Gawley Creek Syenite (Figure 17) straddles the north end of the boundary between Marmora and Madoc townships. Access is provided by Highway 62, north from Madoc and west from Highway 62 to Malone. The body covers an area of approximately 50 km^2.

Geology

The Gawley Creek Syenite lies at the southern end of the Elzevir Terrane of the Grenville Province. The body is roughly square in outline, with dimensions: 5 km long (north to south) and 7 km wide in the north, narrowing slightly to 3.5 km wide in the south. The Gawley Creek body has not been examined in detail and only the general mineralogy has been described in the course of mapping. The rock is a pink biotite-hornblende syenite (Hewitt 1968; Bartlett and Moore 1985). Microcline microperthite and cryptoperthitic oligoclase have interlocking, sutured textures (Hewitt 1968). Hornblende and biotite are secondary minerals and accessories include sphene, apatite, epidote and opaque minerals (Hewitt 1968). The syenite is coarse grained for the most part.

In the area of the Bannockburn Mine at the south end of Marmora Township, the rocks consist of dark grey, coarse grained syenodiorite, composed of oligoclase, biotite, and accessory magnetite, pyrite, apatite, titanite, zoisite and calcite (Hewitt 1968).

Economic Aspects

There are gold deposits near Bannockburn, hosted by quartz veins in the country rocks to the Gawley Creek Syenite (metavolcanics and metapelites)

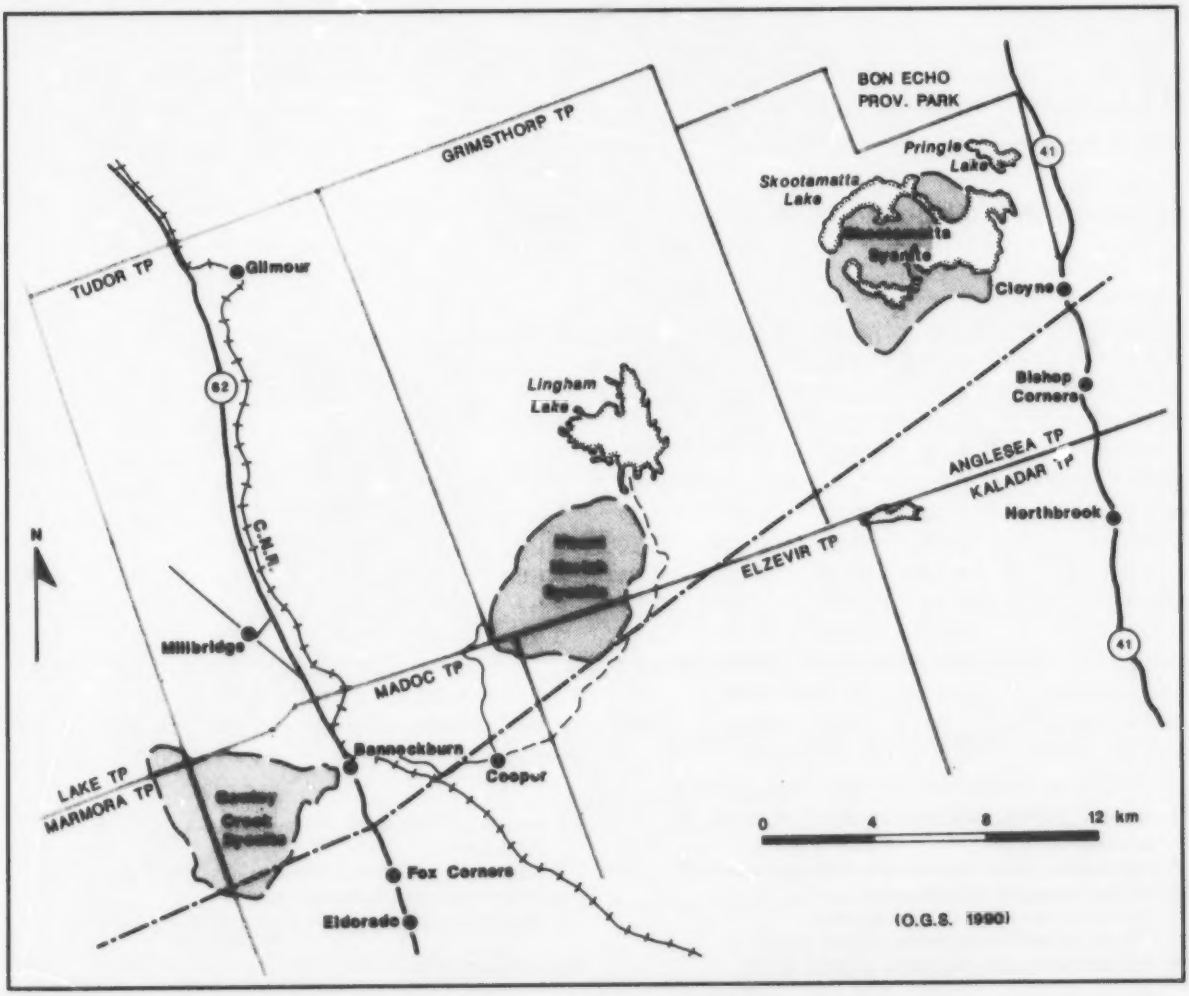


Figure 17. Gawley Creek, Mount Moriah and Skootamatta Syenites.

(Hewitt 1968; Assessment File Records: Mono Exploration Ltd.). There is no known connection between the gold mineralization and the intrusion. A magnetic anomaly occurs over the Gawley Creek syenite, centred over Moss Marsh. Drilling in the 1950s determined that the anomaly could be accounted for by the presence of disseminated magnetite.

Exposure

Exposure is reportedly poor in the south end of Marmora Township (Bartlett and Moore 1985), however mapping suggests that exposure ranges from 10 to 30% (Hewitt 1968; Bartlett and Moore 1985) in this part of the body. There is probably 30 to 50% exposure in the core and on the west side of the pluton (Easton, personal communication).

Geochemistry

Unfortunately, chemical analyses are not available for the Gawley Creek syenite. The mineralogy suggests probable Al_2O_3 content around 20%, and high proportions of feldspar and biotite could provide relatively high total alkali contents.

Mount Moriah Syenite

The Mount Moriah Syenite (Figure 17) lies mainly in Grimsthorpe Township, although the south margin of the body extends into Elzevir Township. The body is accessible by dirt road from Cooper, 17 km north from Madoc. The body covers an area of approximately 25 km^2.

Geology

The Mount Moriah Syenite is a circular intrusion, situated near the south end of the Elzevir Terrane, in the Grenville Province. This body is similar to the Gawley Creek syenite (Hewitt 1968) but again, details of the geology are not provided. The rocks are pink coarse-grained syenite (Hewitt 1968). The general geology is outlined by Brown and Thivierge (1979).

The Mount Moriah Syenite consists of two phases. An earlier augite ± hornblende syenite comprises the bulk of the body, covering a subcircular area of approximately 20 km^2. A later phase occurs at the south end of the body as an arcuate unit, separated from the main mass by a narrow sliver of volcanic rocks.

The main mass consists of potassic feldspar (perthitic orthoclase and microperthitic microcline), lesser plagioclase (albite), augite, and 5 to 10% hornblende and biotite (Easton, personal communication). The rock is coarse grained, with large irregularly shaped feldspars, surrounding the other minerals. Grain boundaries are typically sutured. Hornblende, biotite and minor magnetite occur as primary grains, and as alteration products of augite. Accessory minerals include apatite, zircon, allanite, magnetite, epidote and calcite. Quartz is locally present in very small amounts (less than 2%) and occurs interstitially as very fine grains. Some of the apatite and zircon grains form inclusions in the feldspars, calcite occurs along fractures and some of the feldspar is epidotized.

The smaller mass to the south has a lower mafic content, with a colour index of only five. This syenite is medium grained and consists essentially of perthitic microcline, with approximately 10% albite plagioclase, minor biotite and quartz. The microcline occurs as large, irregularly shaped grains. Grain boundaries of all the minerals are variably sutured except for the plagioclase which occurs as euhedral to subhedral grains. Accessory minerals include zircon, apatite, allanite, magnetite and hematite. As within the main mass, zircon and apatite occur as inclusions within the feldspars. Magnetite and hematite occur interstitially and along grain boundaries.

Quartz monzonite and granite occur as pods and lenses with the southern unit and as narrow (usually 1 to 2 m wide) dikes throughout the Mount Moriah Syenite. Microcline, orthoclase, albite, quartz (up to 15% in the granite) and biotite in varying proportions, make up the mineralogy of these units.

Economic Aspects

The Mount Moriah Syenite was studied by Atomic Energy of Canada, to determine the structural integrity of the body. Their study was not conclusive, but outlines the major faulting, fracturing and joint patterns which are all related to late (post-Ordovician) regional faulting (Brown and Thivierge 1979).

Exposure

The larger, circular mass to the north is reportedly well exposed, particularly along several ridges, with up to 40% outcrop. The southerly mass is less well exposed and is obscured in several places by low-lying swampy areas. (Brown and Thivierge 1979).

Geochemistry

Unfortunately there is no chemical data available on the Mount Moriah Syenite. High proportions of feldspars are suggestive of relatively high $Al_2O_3+CaO+Na_2O+K_2O$. As well, the relative paucity of mafic minerals, and their apparent mode of occurrence, could contribute to relatively simple separation of a concentrate.

Skootamatta Syenite

The Skootamata Syenite (Figure 17) is a large, roundish body centred in Anglesea Township. The body covers an area of approximately 30 km^2, and underlies a large part of Skootamatta and Sheldrake Lakes. Access is provided by county roads east from Highway 41 and the town of Cloyne.

Geology

The Skootamatta Syenite is centrally located in the Elzevir Terrane. The body is slightly elongate to the south-southwest with a length of 7.5 km and a width of 4 to 6 km. The Skootamatta Syenite has not been studied in detail. Mapping of Anglesea Township was undertaken by Meen (1944) and was later followed up by the work of Moore and Morton (1986) who cover only the far eastern part of the pluton. These two sources provide all the known information on the Skootamatta body.

The syenite is a light grey to pale pink, massive equigranular rock. There is a weak foliation in places. The syenite is coarse- to medium-grained for the most part with a minor decrease in grain size towards the contacts. Mineralogy consists of microcline, albite and biotite with accessory sphene, apatite and magnetite. The very low colour index is suggestive of a mafic content of 5% or less. Quartz is present in very minor amounts, varying from trace to 5%, and can only be detected in thin section (Moore and Morton 1986).

Economic Aspects

Were nepheline to be detected, this coarse grained, homogeneous, leucocratic body could have substantial industrial mineral potential. At present, there is no known mineralization associated with this body.

Exposure

Map 2499 (Moore and Morton 1986) shows that the east side of the body is only well exposed along the north shore of Skootamatta Lake. Smaller exposures occur on the eastern side of Big Island, and along the cottage road that runs along the south end of Skootamatta Lake.

Geochemistry

There is no chemical data available on the Skootamatta Syenite. Unfortunately the mineralogy is not described modally and possible Al_2O_3 and $CaO+Na_2O+K_2O$ potential is difficult to estimate. The low mafic content and homogeneous texture are both favourable qualities for industrial mineral use.

Burns Lake Syenite

The Burns Lake Syenite is an oval body, situated in Griffith Township (Figure 18). The body can be accessed by Highway 41, north from Griffith, or east from Renfrew for 15 km on Highway 132. The body covers an area of approximately 25 km^2.

Geology

The Burns Lake Syenite, is an oval 6 km long (southeast) and 4 km wide (northeast). The complex consists of a melanocratic, syenite core and a leucocratic rim (Themistocleous 1981). The intrusion lies at the north margin of the Elzevir Terrane in the Grenville Province of Ontario. The leucocratic syenite which occurs as an arc surrounding the northeast corner of the intrusion (Themistocleous 1981) is of interest with respect to alumina and alkali potential. The syenite consists of: perthitic feldspar 15 to 40%, orthoclase feldspar 6 to 40%, albite plagioclase 4 to 20%, biotite 5 to 20%, augite 0 to 10% and hornblende 4 to 10% (Themistocleous 1981). Accessory minerals include magnetite, sphene, apatite, carbonate, and zircon (Themistocleous 1981). The leucocratic portion of the intrusion is somewhat heterogeneous, with inclusions of feldspathic arenite, amphibolite gneiss, and marble (Themistocleous 1981). There are also cross-cutting, north-northeast trending diabase, diorite- and granite-pegmatite dikes which contribute to the heterogeneity of the body.

Economic Aspects

Assessment files show no record of exploration activity. Mineral occurrences of magnetite+titanite +pyrite+anatase, scapolite+apatite, and anatase+tourmaline are indicated on Map 2454 (Themistocleous 1981). Unfortunately there is no discussion of these mineral occurrences.

Exposure

The rocks of this complex are relatively well exposed judging from the absence of overburden indicated on Lumbers' map (1982). Themistocleous' map (1981) indicates that the southeastern two thirds of the complex are well exposed and a secondary road east from Highway 41, which transects the body, has outcrop along its entire length (Themistocleous 1981).

Geochemistry

Themistocleous (1981) provides 11 analyses of alkalic syenites from the Khartum area, Table 27 gives the nine of which are from the Burns Lake Complex. Samples of the buff, massive- to coarse-grained syen-

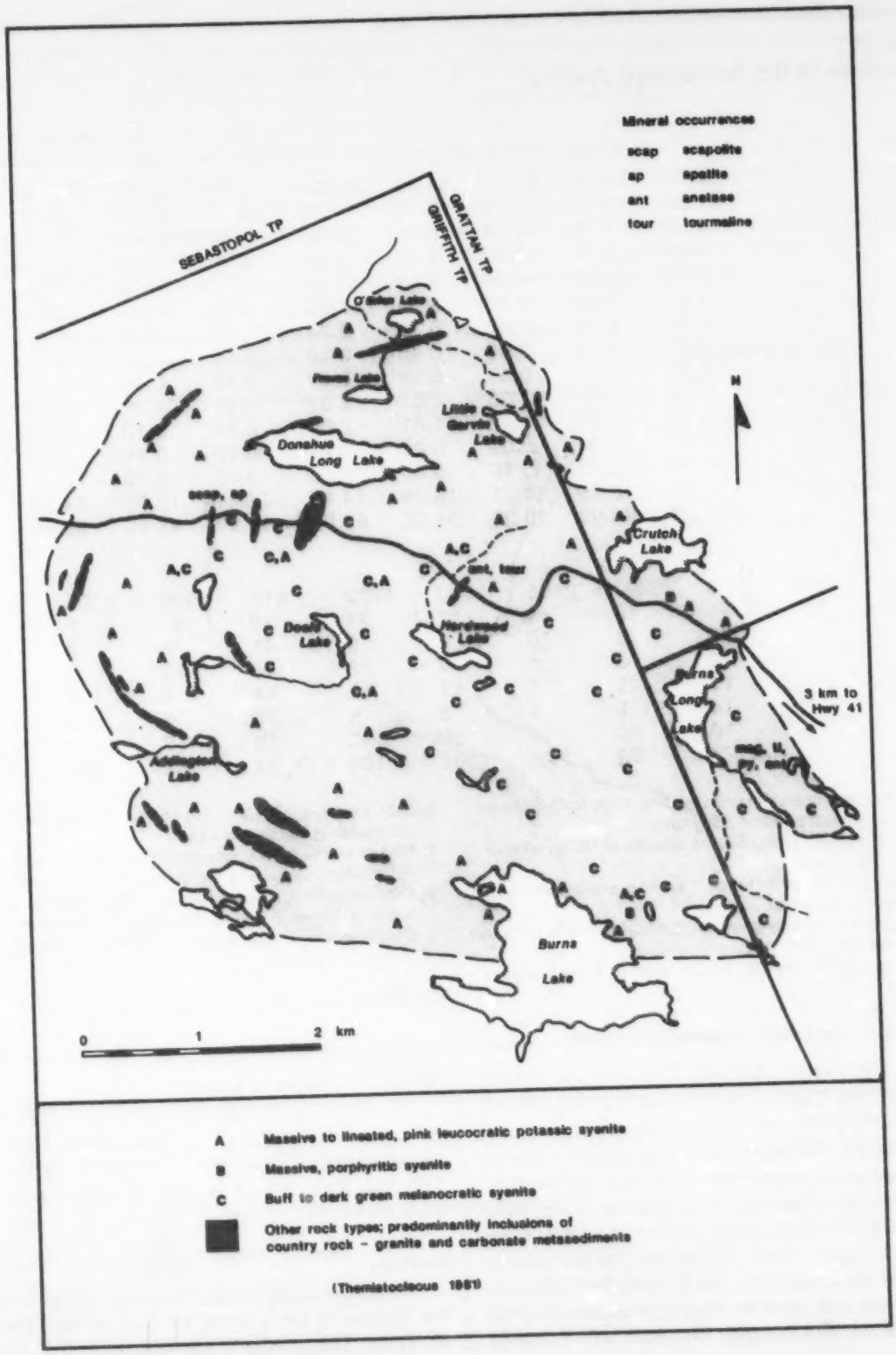


Figure 18. Burns Lake Syenite.

Table 27
Chemistry of the Burns Lake Syenite

	1	2	3	4	5	6	7	8	9
SiO_2	54.70	52.50	50.90	51.40	42.90	51.00	48.50	51.10	52.60
Al_2O_3	21.00	19.10	17.70	18.70	14.00	20.20	16.00	16.60	21.80
Fe_2O_3	6.52	7.18	9.24	8.11	15.90	7.44	11.10	5.63	5.23
MgO	3.07	2.79	3.70	3.45	5.98	2.96	3.72	3.20	2.50
CaO	7.37	3.80	4.10	4.58	7.20	8.07	8.09	9.70	6.71
Na_2O	5.71	3.22	4.02	3.65	1.89	5.08	2.94	2.87	5.26
K_2O	0.74	6.73	6.09	6.15	5.37	1.66	5.68	5.79	2.92
LOI	0.40	0.40	0.60	0.40	0.70	1.10	0.80	1.10	1.90
CO_2	0.20	0.13	0.33	0.12	0.52	0.92	0.56	0.88	0.86
TiO_2	0.70	1.21	1.63	1.37	2.51	0.81	1.36	1.00	0.83
P_2O_5	0.24	1.05	1.22	1.01	2.05	0.43	0.13	1.30	0.14
S	0.01	0.04	0.06	0.06	0.25	0.06	0.11	0.04	0.07
MnO	0.09	0.05	0.10	0.08	0.13	0.10	0.13	0.07	0.06
$CaO+Na_2O+K_2O$	13.82	13.75	14.21	14.38	14.46	14.81	16.71	18.36	14.89
TOTAL	100.20	98.00	99.30	98.90	98.60	98.90	99.60	98.30	100.00
ppm									
BA	270	5800	2400	3900	4000	810	3300	6500	1400
CO	19	19	14	17	34	30	30	8	13
CR	35	5	10	9	9	41	5	5	31
CU	10	8	5	9	22	12	38	5	8
LI	15	18	15	12	19	14	6	7	10
NI	14	5	5	5	5	22	8	5	10
PB	10	20	19	19	10	10	17	15	15
ZN	77	78	126	102	164	86	152	60	72

1. Buff, massive, coarse-grained syenite, 1 km north of Burns Lake, 1 km west of Burns Long Lake.
2. Coarse-grained, pink, foliated syenite, 0.15 km west of Burns Long Lake.
3. Coarse-grained, pink, foliated syenite, southwest of Donahue Long Lake.
4. Fine-grained, weakly gneissic, buff syenite, 0.8 km south of Hardwood Lake.
5. Buff, porphyritic syenite, 0.3 km west of Burns Long Lake.
6. Buff, massive syenite, 1 km north of Burns Lake, 1 km southeast of Hardwood Lake.
7. Fine-grained, weakly gneissic, grey syenite, southwest of Donahue Long Lake, northwest of Dools Lake.
8. Coarse-grained, weakly foliated, white potassic syenite, south of Donahue Long Lake, north of Dools Lake.
9. Coarse-grained, buff, massive syenite, 0.6 km southwest of Hardwood Lake.

(Themistocleous 1981)

ite have Al_2O_3 values just over 20%, whereas the rest of the samples from the Burns Lake Syenite contain less than 20% Al_2O_3 and hence represent less prospective parts of the complex. Total alkali content ($CaO+Na_2O+K_2O$) ranges from 13.28 to 18.36 weight %, and alkali content appears to be highest in the rocks of the leucocratic rim syenite. It should be noted that rocks with higher Al_2O_3 values are not necessarily samples of the leucocratic rim syenite, but rather the melanocratic syenite of the core. Consequently, areas throughout the intrusion may have economic potential.

Mount St. Patrick Syenite

The Mount St. Patrick Syenite (Figure 19) is situated in the north half of Brougham Township, approximately 25 km east of Renfrew, on Highway 132. The body covers an area of approximately 25 km^2.

Geology

The Mount St. Patrick Syenite occurs near the northern margin of the Elzevir Terrane, in the Grenville Province. The syenite is medium- to coarse-grained, predominantly perthite-biotite-hornblende. Modes are:

porphyritic microperthite (70 to 85%), biotite (2 to 15%), hornblende (0 to 10%), and albite to oligoclase plagioclase (0 to 10%) (Themistocleous 1981). Accessory minerals include orthoclase, augite, scapolite, sphene, zircon, apatite and carbonate (Themistocleous 1981). Coarse aggregates (up to 5 cm long) of microperthite phenocrysts, with embayed grain boundaries, comprise 70 to 100% of the syenite and mafic minerals, some feldspar and the accessory minerals make up the ground mass (Themistocleous 1981).

There are minor melanocratic units within the syenite which contain up to 50% mafic minerals and less than 10% perthite phenocrysts (Themistocleous 1981). The extent of these melanocratic zones is important in that they represent areas of depleted alumina and alkalies.

Zones of finer grained, lineated syenite occur where there are narrow shear zones crosscutting the body (Themistocleous 1981).

Economic Aspects

Molybdenum mineralization, as patches of disseminated molybdenite, occur in the calcareous metasediments at the margins of syenite. Low grade and small size of mineralized patches do not justify development (Carter et al. 1980).

Geochemistry

There is no available chemical data for the por-

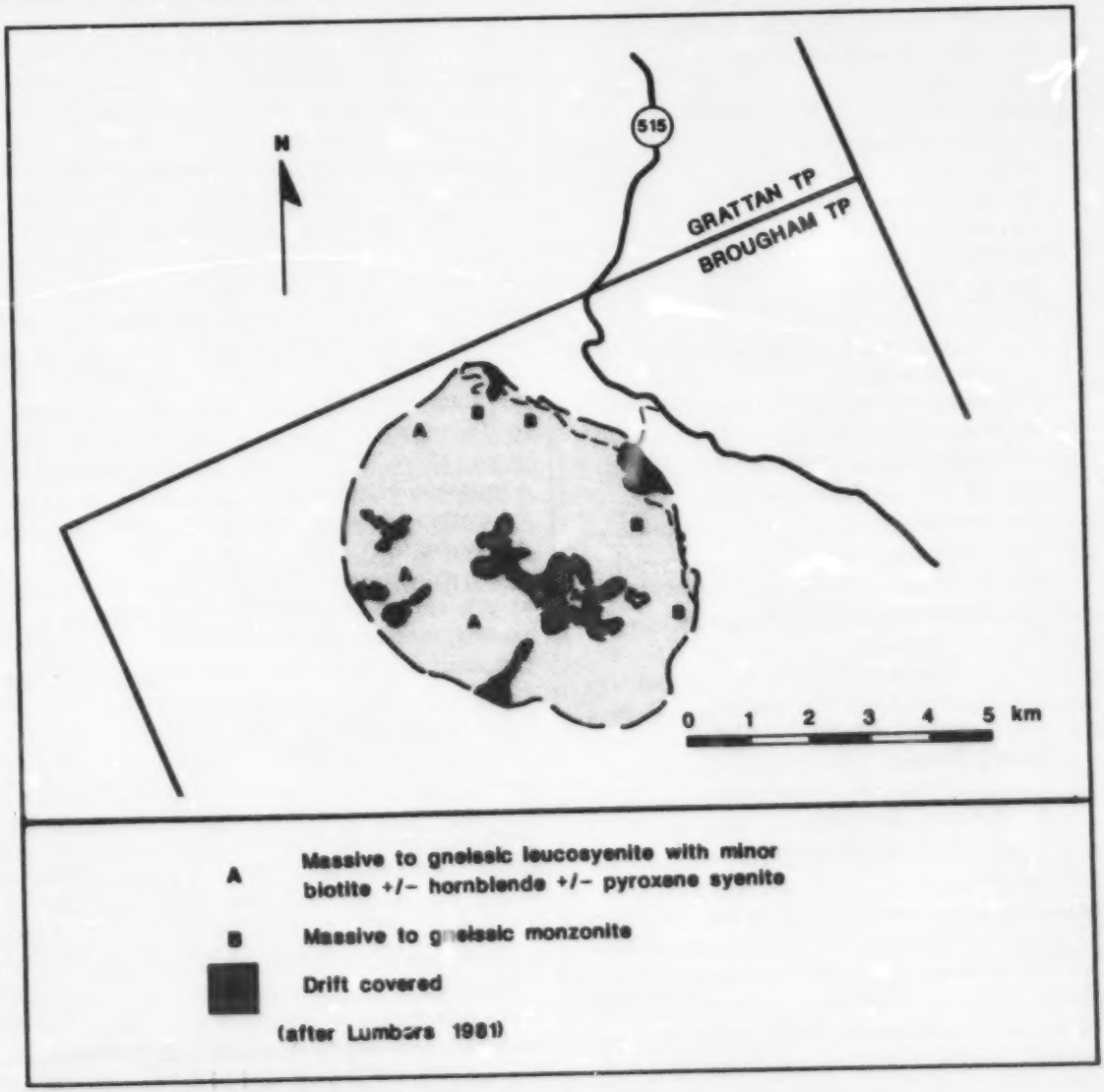


Figure 19. Mount St. Patrick Syenite.

phyritic syenite of the Mount St. Patrick intrusion. Themistocleous (1981) provides 2 analyses of the melanocratic phase of the Mount St. Patrick Syenite and these samples are low in Al_2O_3, relative to expected values for the poyphyritic syenite. Total alkali content in the melanocratic rocks averages 15.93 weight %. Mineralogy of the porphyritic syenite is suggestive of Al_2O_3 probably over 20%.

Anorthosites

Anorthosite descriptions, grouped according to geological setting are listed as follows:

- Superior and Southern Province Anorthosites
  - Proterozoic: East Bull Lake Pluton
  - Archean: Bad Vermilion Lake Anorthosite
    - Shawmere Anorthosite Complex
- Grenville Anorthosites
  - Central Gneiss Belt — North half
    - Fall Lake Anorthosite
    - River Valley Anorthosite
    - Red Deer Anorthosite
    - Pickerel Complex
    - St. Charles Anorthosite
    - Mercer Anorthosite
    - Eau Claire Anorthosite
  - Central Gneiss Belt — South half
    - Arnstein Anorthosite
    - Raganooter Anorthosite
    - Whitestone Anorthosite
    - Parry Island Anorthosite
    - Moon River and Twelve Mile Bay anorthosites
    - Little Lake Anorthosite
    - Head River and Smudge Lake anorthosites
  - Central Metasedimentary Belt
    - Bancroft Terrane
      - Allsaw Anorthosite
      - Percy Lake Anorthosite
      - Farquhar Lake Complex
    - Elzevir Terrane
      - Elbow Lake Anorthosite
    - Sharbot Lake Terrane
      - Wilkinson Anorthosite

Superior and Southern Province Anorthosites

Proterozoic

East Bull Lake Gabbro-Anorthosite Pluton (41J/08)

The East Bull Lake intrusion is situated 35 km east of Elliot Lake and covers approximately 20 km^2 in Gerow and Boon townships. Access is provided by highway 553 (2 lane, unpaved road), 27 km north of the Trans Canada Highway 1, and the town of Massey. High proportions of feldspar are present in the anorthosite unit which covers an area of approximately 3 km^2.

Geology

The East Bull Lake pluton (Figure 20) is Early Proterozoic in age (2480 Ma old, McCrank et al. 1989) and intrudes metavolcanic rocks of the Superior Province. The body is sigmoidal, elongate from east to west, with maximum dimensions of 13 km by 3.5 km. James and Born (1985) refer to the body as a lopolith ... "a large, concordant, typically layered, igneous intrusion, of plano-convex or lenticular shape, that is sunken in its central part" (Bates and Jackson 1987). The East Bull Lake body exhibits concentric layering with an outer anorthosite, and progressively more mafic units (leuconorite, norite and troctolite) towards the centre (Figure 20). Anorthosite occurs as a unit 500 to 1000 m wide, disjointed, ribbon shaped, shallow dipping (5° to 30°), and encircling the rest of the body. Anorthosite blotches and regular bands occur within the rhythmic-layered gabbro/leuconorite (Moore and Armstrong 1943; McCrank et al. 1989).

The anorthosite is 90% plagioclase feldspar and 1 to 10% augite. The plagioclase is commonly coarse grained, inequigranular to prismatic, and ranging in composition from labradorite to bytownite (McCrank et al. 1989). Calcic amphiboles, epidote, biotite, adularia, quartz, calcite, sphene, pyrite, pyrrhotite, chalcopyrite, serpentine, chlorite, pumpellyite, laumontite, gypsum, clays and iron hydroxides are accessory minerals resulting from alteration and upper greenschist grade metamorphism (McCrank et al. 1989; Moore and Armstrong 1943). Calcic amphiboles, biotite and epidote commonly form cores and coronas to plagioclase. Alteration minerals infill abundant fractures and joints (McCrank et al. 1989).

Mafic dikes are numerous, estimated to occupy 20% of the pluton volume (McCrank et al. 1989). The geologic map provided by McCrank et al. (1989) suggests that dikes are less abundant in the anorthosite unit. Dike density must therefore be considered when estimating industrial mineral potential.

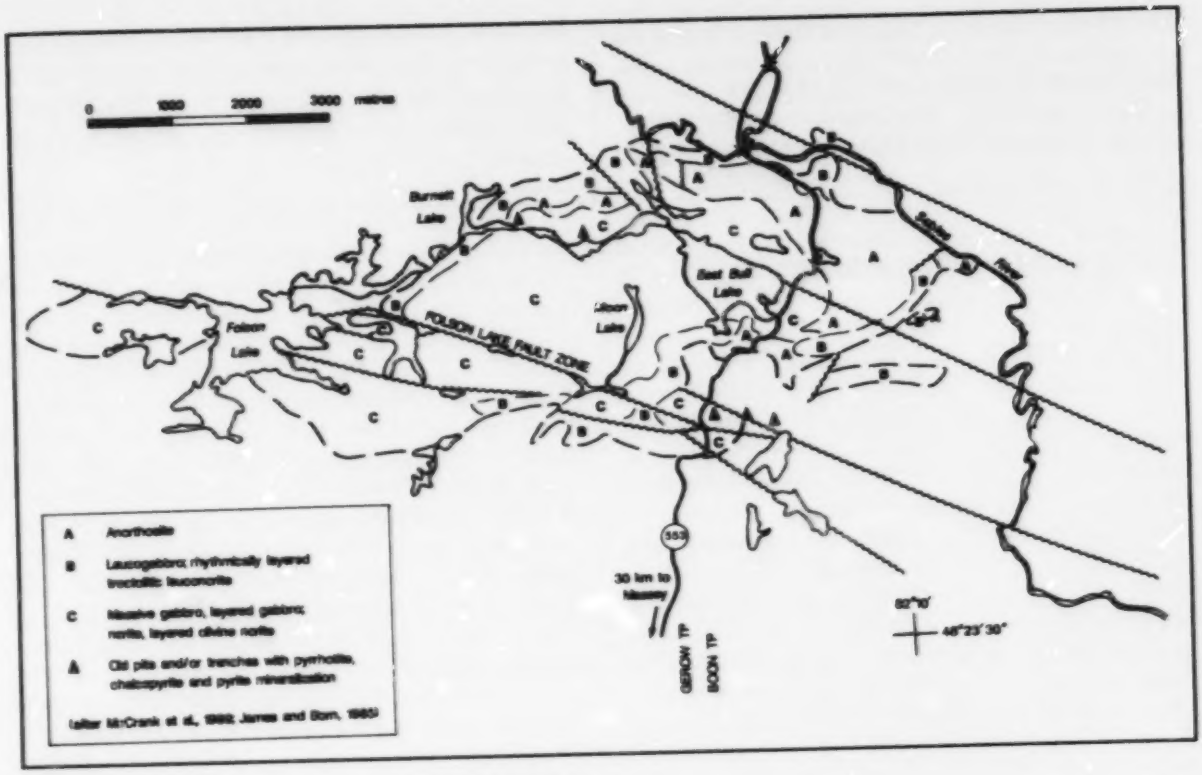


Figure 20. The East Bull Lake Gabbro Anorthosite.

The Folson Lake Fault cuts the south part of the intrusion. Grain size reduction and intense alteration characterize the rocks adjacent to the Folson Lake Fault and Al_2O_3 potential will be adversely affected by these areas of more intense alteration. Dike density and the extent of mineral replacement of feldspars will be factors strongly affecting the industrial mineral potential of these rocks.

Economic Aspects

Nickel and copper mineralization occurs as disseminated to massive pyrrhotite, chalcopyrite, pyrite and minor magnetite along localized shears (Moore and Armstrong 1943). Old pits and trenches are common along west-northwest trending shears and faults.

Atomic Energy of Canada Limited has extensively studied the East Bull Lake Intrusion, as part of their nuclear fuel waste management program. (See McCrank et al. 1983, 1987; Kamineni et al. 1984).

Exposure

Exposure of the East Bull Lake body is reported to be excellent. The topography is dominated by 30 to 60 m high hills and mapping indicates outcrop density to be 80% (Moore and Armstrong 1943). Highway 553 cuts through the basal anorthosite unit in the northern part of the body and the easterly anorthosite exposures are accessible via the Sables River.

Geochemistry

Three sources reported geochemical data for the East Bull Lake intrusion. James and Born (1985) give analyses for eight samples, grouped according to cumulate mineral phases, e.g., olivine-plagioclase cumulates, pyroxene-plagioclase cumulates and ultramafic cumulates. Compositions can vary substantially within this grouping, although anorthosites are probably referred to as plagioclase cumulates, and it is unknown which of the samples may represent the anorthosite unit. Chemical data is also reported by McCrank et al. (1989). This data is not listed by lithology either, but rather by magmatic cycle. Correlations between the chemistry and stratigraphic section of McCrank et al. (1989) suggest that analyses given for cycle 1 magmatism are representative of the basal anorthosite unit. Selected analyses from James and Born (1985) and McCrank et al. (1989) are given in Table 28, however, it is uncertain how well these analyses represent the anorthosite bulk chemistry. Two analyses from the PETROCH database are also reported in Table 28.

BAD VERMILION LAKE COMPLEX (52C/NE)

The Bad Vermilion Lake Complex is situated approximately 50 km east of Fort Frances in northern Ontario. The body is accessible via the town of Mine Centre on Highway 11. It covers an area of 100 km^2, straddling Vermilion Lake and extending south to Seine Bay on Rainy Lake.

Table 28
Chemistry of the East Bull Lake Pluton

wt.%	A	B	C	D	EI-6	DL-1
SiO_2	49.70	48.70	50.30	46.82	50.67	46.90
TiO_2	0.38	0.42	0.18	0.18	0.32	0.14
Al_2O_3	20.20	21.70	22.40	13.51	22.17	22.67
Fe_2O_3	7.86	7.21	1.47	1.62	6.72	8.24
FeO			2.18	13.50		
MnO	0.13	0.11	0.06	0.25	5.09	0.13
MgO	6.30	6.59	5.89	7.89		
CaO	11.70	11.10	10.90	8.55	11.24	12.37
Na_2O	2.42	2.06	3.02	0.57	2.16	1.39
K_2O	0.23	0.37	1.24	0.06	0.69	0.24
P_2O_5	0.06	0.06	0.01	0.01	0.05	0.03
CO_2					0.30	0.25
S					0.01	0.02
H_2O+			2.30	0.50		
H_2O-						
TOTAL			97.26	100.29	99.29	98.59
LOI	1.30	1.70				
SP.GR.	2.88	2.86				
ppm						
Ba	140	170			148	29
Co	38	40			n.a.	n.a.
Cr	384	196			75	70
Cu					18	44
Li					8	11
Ni	103	183			156	284
Pb					25	17
Zn					68	69
Rb					14.5	7
Sr					387	257
Y					13.4	4
Zr					60	21

A: PETROCH data, sample of anorthositic gabbro, from massive zone; sample submitted by P.J. Whittaker.
B: PETROCH data, sample of pyroxenite from lensoid unit within massive anorthositic gabbro; sample submitted by P.J. Whittaker.
C: Pulse 1, anorthositic unit @ 620.4 m depth, borehole EBL-1 (McCrank et al. 1989)
D: Pulse 1, anorthositic unit @ 661.4 m depth, borehole ELB-1 (McCrank et al. 1989)
EI-6: Pyroxene-plagioclase cumulate (James and Born 1985)
DL-1: Olivine-plagioclase cumulate(James and Born 1985)

Geology

The Bad Vermilion Lake intrusion (about 2700 Ma; Ashwal et al. 1983) lies within Archean supracrustal rocks of the Superior Province. The complex is an anorthositic to gabbroic, differentiated sill with the more differentiated anorthositic rocks in the northeast and melagabbro to gabbro in the southwest of the complex (Poulsen 1984). The anorthosite forms a distinct mappable unit containing minor altered and gabbroic phases, often present as decimetre scale layering (Ashwal et al. 1984).

The anorthosite consists of large (1 to 30 cm), equidimensional, euhedral to subhedral plagioclase phenocrysts of bytownite to anorthite composition (An_{80-95}) with less than 5% mafic content in places (Ashwal 1983; Phinney et al. 1988). Greenschist metamorphism and alteration have resulted in localized replacement of plagioclase by fine grained inclusions and aggregates of zoisite plus other epidote group minerals, minor albite, paragonitic white mica and rare pumpellyite (Ashwal et al. 1983). Harris (1974) describes completely altered plagioclase phenocrysts with abundant subparallel open fractures.

The matrix is made up of finer grained, predominantly mafic minerals, commonly chlorite, zoisite, amphibole (tremolite-actinolite to ferrohastingsite), albite, calcite and quartz (Harris 1974). Remnant primary pyroxene phenocrysts are rare (Phinney et al. 1988). Chloritic shears 1 cm to 1 m in width crosscut the anorthosite along the southern margin in Seine Bay (Harris 1974). In some localities the interstitial mafic material consists of large, individual crystals of actinolite or low-Al hornblende (Ashwal et al. 1983).

A more homogeneous gabbro, the southern gabbro, intrudes the Bad Vermilion Lake anorthosite. Exposures of metabasalt as large as 3 m by 15 m, occur in the central part of the complex and may be assimilations or interfingerings of country rocks (Harris 1974; Poulsen 1984).

Economic Aspects

Numerous mineral occurrences are present in the Bad Vermilion Lake Complex. The more significant occurrences/deposits are indicated on the map. For more detailed information see Poulsen (1984). There are several Fe-Ti-V oxide occurrences in the upper levels of the intrusion, occurring as lenses of massive to disseminated magnetite ± ilmenite ± apatite ± rutile (Poulsen 1984) (Figure 21). Minor copper mineralization occurs as disseminated chalcopyrite (+ pyrite,

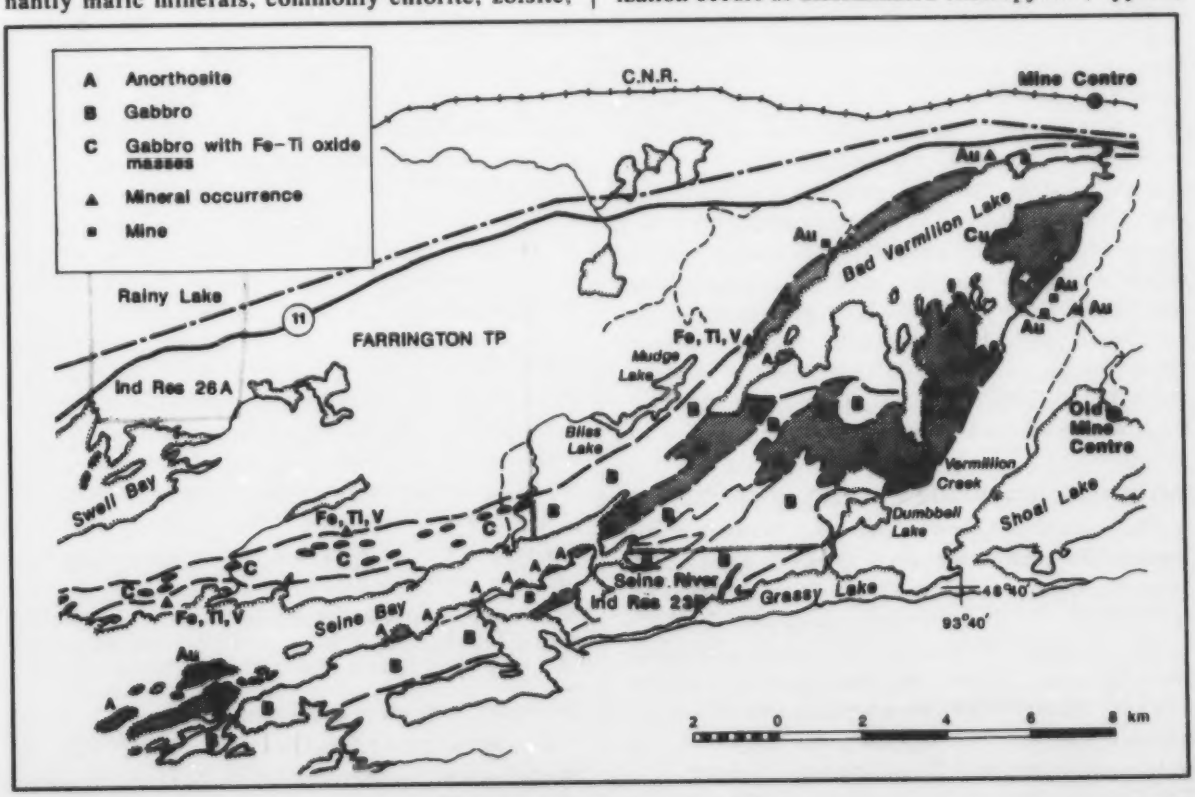


Figure 21. Bad Vermilion (sic) Lake Anorthosite.

pyrrhotite, pentlandite) at the base of the intrusion (Figure 21). There are several gold occurrences stratigraphically below the sill, just to the east of the Bad Vermilion Lake Complex, near the town of Old Mine Centre (see Poulsen 1984).

Exposure

Anorthosite is well exposed along the shores of Bad Vermilion Lake, the southern shores of Seine Bay and on the Seven Sister Islands. Outcrop density in the bush is moderate, comprising 15 to 20% of the areal extent of the anorthosite. Exposures of massive anorthosite around Bad Vermilion Lake consist of 100% plagioclase (Ashwal 1983) and are therefore, of particular interest.

Geochemistry

Ashwal et al. (1983) collected 400 samples from the complex and surrounding rocks. In total, nine analyses of the anorthosite, altered anorthosite and gabbroic anorthosite are published. All nine samples contain more than 20% Al_2O_3, averaging 27.3 weight % (Table 29). Total alkali contents are relatively high for the Bad Vermilion body, averaging 17% for nine samples. Sample locations for these rocks are given by Ashwal et al. (1983). Many anorthosite samples analyzed by Ashwal were collected from the Seven Sisters Islands in Seine Bay at the south end of the complex. Unfortunately these samples represent material furthest from road and rail transport (20 km).

Unfortunately, there are no analyses given for the massive anorthosite. On the southeastern shore of Bad Vermilion Lake massive anorthosite is exposed over an area of at least 5 km^2. Although there is no geochemical data from this part of the body, descriptions of the anorthosite suggest good potential, with high plagioclase proportions (95 to 100%) (Phinney et al. 1988; Ashwal et al. 1983), minimal deformation and alteration, and good road and rail access.

Shawmere Anorthosite Complex (41O/NW)

The Shawmere Complex is located between Chapleau and Foleyet, in the following townships: Oates, Lincoln, Lemoine, Folyet, Alcorn, Paul, Warren, Carty, Collins, Murdock, Evans, Pinogami, Chewitt, Sandy, Hellyer, Crocket, Raney, Camey, Gallacher, McNaught and Lackner. The complex covers an area 800 km^2. Access is provided by Highway 101 which transects the body between Chapleau and Foleyet as well as secondary road branching from Highway 101. The Canadian National Railway crosses the northeast end of the complex.

Geology

The Shawmere Complex (Figure 22) is an Archean body situated at the southern end of the Kapuskasing Structural Zone, in the Superior Province. The complex trends northeasterly, with a length of 84 km and maximum width of 24 km. Strong regional metamorphism and deformation are imprinted on the surrounding rocks.

The complex exhibits wide compositional variability. There is an anorthositic core which contains leuco- to mela- gabbroic zones. Gabbro and troctolite are concentrated to the north and south of the core units and garnetiferous amphibolite occurs around the margins (Riccio 1979). It is the anorthositic core of the complex which represents the highest Al_2O_3 and alkali potential.

Anorthosite occurs in layers, often gradational to gabbro. Thicknesses of actual anorthosite units are estimated at 300 m and comprise approximately 50% of complex (Thurston et al. 1977). Lithological layering is often accompanied by textural variations. The plagioclase textures in the anorthosite range from recrystallized granoblastic (1 to 5 cm diameter), to cataclastic, to relict megacrystic (i.e., crystals up to 8 to 13 cm by 45 cm) (Riccio 1979; Thurston et al. 1977). Plagioclase compositions are labradorite to bytownite, An_{60-85} (Thurston et al. 1977). Garnet, pyroxene and amphibole coronas occur around the plagioclase (Riccio 1979; Thurston et al. 1977). Matrix material varies in texture, composition, and proportion (5 to 50%). Plagioclase, hornblende, cummingtonite, anthophyllite, hypersthene, augite and garnet with accessory sphene, rutile, and epidote occur as fine grained interstitial material and as coarse patches (Thurston et al. 1977). Less common accessory minerals include sapphirine and Al-spinel (Phinney et al. 1988). Primary olivine, orthopyroxene and clinopyroxene occur in the least deformed parts of the complex (Phinney et al. 1988). Minor crosscutting shears are composed of scapolite, epidote (clinozoisite), carbonate, quartz and minor hematite along with crushed feldspar (Thurston et al. 1977).

Other crosscutting features include semiconcordant sheets of quartzofeldspathic gneisses (Thurston et al. 1977), quartz-hornblende pegmatites and olivine diabase dikes (Riccio 1979).

Economic Aspects

Geological maps of the Shawmere Complex show no mineral occurrences within the body. However, sampling of the Shawmere anorthosite has been undertaken as a prospective alumina resource.

Table 29
Chemistry of the Bad Vermilion Lake Complex

	1	2	3	4	5	6	7	8	9
SiO_2	48.70	49.17	47.57	46.62	46.51	44.78	46.04	45.17	42.97
TiO_2	0.04	0.11	0.07	0.19	0.12	0.16	0.17	0.17	0.33
Al_2O_3	29.50	30.13	31.06	29.99	27.14	28.14	23.21	20.67	25.69
Fe_2O_3	0.16	0.06	0.36	0.64	1.57	1.42	3.00	2.23	3.00
FeO	0.18	0.92	0.48	0.62	1.86	0.72	2.19	3.29	3.07
MnO	0.01	0.02	0.01	0.01	0.04	0.05	0.09	0.09	0.06
MgO	0.60	1.10	0.93	0.50	2.61	1.20	5.78	6.68	5.22
CaO	14.18	12.20	14.93	15.60	14.42	17.74	13.46	13.99	11.25
Na_2O	3.81	3.42	2.91	3.00	1.70	2.90	0.93	1.13	2.30
K_2O	0.29	0.83	0.12	0.21	0.06	0.10	0.00	0.01	1.42
P_2O_5	0.03	0.03	0.03	0.04	0.03	0.05	0.02	0.03	0.03
LOI	2.48	2.11	1.65	2.31	3.83	2.19	4.68	7.57	4.57
TOTAL	99.98	100.10	100.12	99.73	99.79	99.45	99.57	101.03	99.91
$CaO+Na_2O+K_2C$	18.28	16.45	17.96	18.81	16.81	20.74	14.39	15.13	14.97
ppm									
Cr	8.80	1.00	0.08	1.00	159.00	1.30	570.00	400.00	42.00
Co	19.30	12.20	46.20	20.10	27.50	19.20	58.60	34.20	27.90
Ni	-	14.00	-	-	25.70	-	98.00	126.00	39.00
Rb	-	-	-	3.0	-	2.0	-	-	30.0
Sr	200.0	300.0	150.0	-	175.0	150.0	100.0	150.0	-
La	0.530	0.870	1.130	4.160	0.340	1.050	-	0.790	1.740
Ce	0.940	1.780	1.980	7.410	0.929	-	1.560	1.460	4.990
Nd	-	0.720	-	2.700	-	1.060	-	-	3.600
Sm	0.063	0.190	0.190	0.360	0.230	0.280	0.370	0.232	1.160
Eu	0.303	0.370	0.300	0.380	0.270	0.410	0.270	0.206	0.489
Tb	0.008	0.033	0.022	0.044	0.057	0.059	0.093	0.050	0.255
Yb	-	0.090	-	0.170	0.220	0.230	0.440	-	1.080
Lu	-	0.014	0.015	0.030	0.040	0.040	0.080	0.024	0.170
Sc	0.275	1.430	1.130	2.420	16.080	2.350	33.570	18.170	21.500
Hf	-	0.10	0.10	0.40	17.00	0.20	0.20	2.10	0.30
Ta	1.40	0.60	2.70	1.00	1.20	1.00	1.50	0.40	0.80
Th	-	0.05	0.20	0.20	-	0.05	0.10	-	0.20
U	0.40	0.10	1.00	0.10	0.50	0.40	0.60	-	-
Cs	0.10	3.10	0.20	0.60	0.40	1.00	0.80	0.40	0.70
Sc/Sm	4.40	7.50	5.90	6.70	69.90	8.40	90.10	78.30	18.50

1. Fresh anorthosite, containing coarse (up to 5 cm) plagioclase
2. Anorthosite band in oxide rich gabbro; plagioclase 1 cm in size, with mafic matrix
3. Fresh anorthosite with coarse grained plagioclase (up to 10 cm)
4. Fresh anorthosite, plagioclase 1-2 cm, epidote and chlorite
5. Fresh anorthosite, minor epidote, sericite, chlorite and calcite
6. Completely altered anorthosite, coarse zoisite, epidote, chlorite, calcite, albite, quartz.
7. Altered gabbroic anorthosite
8. Altered gabbroic anorthosite
9. Altered rock from interlayered anorthosite-gabbro (Ashwal 1983)

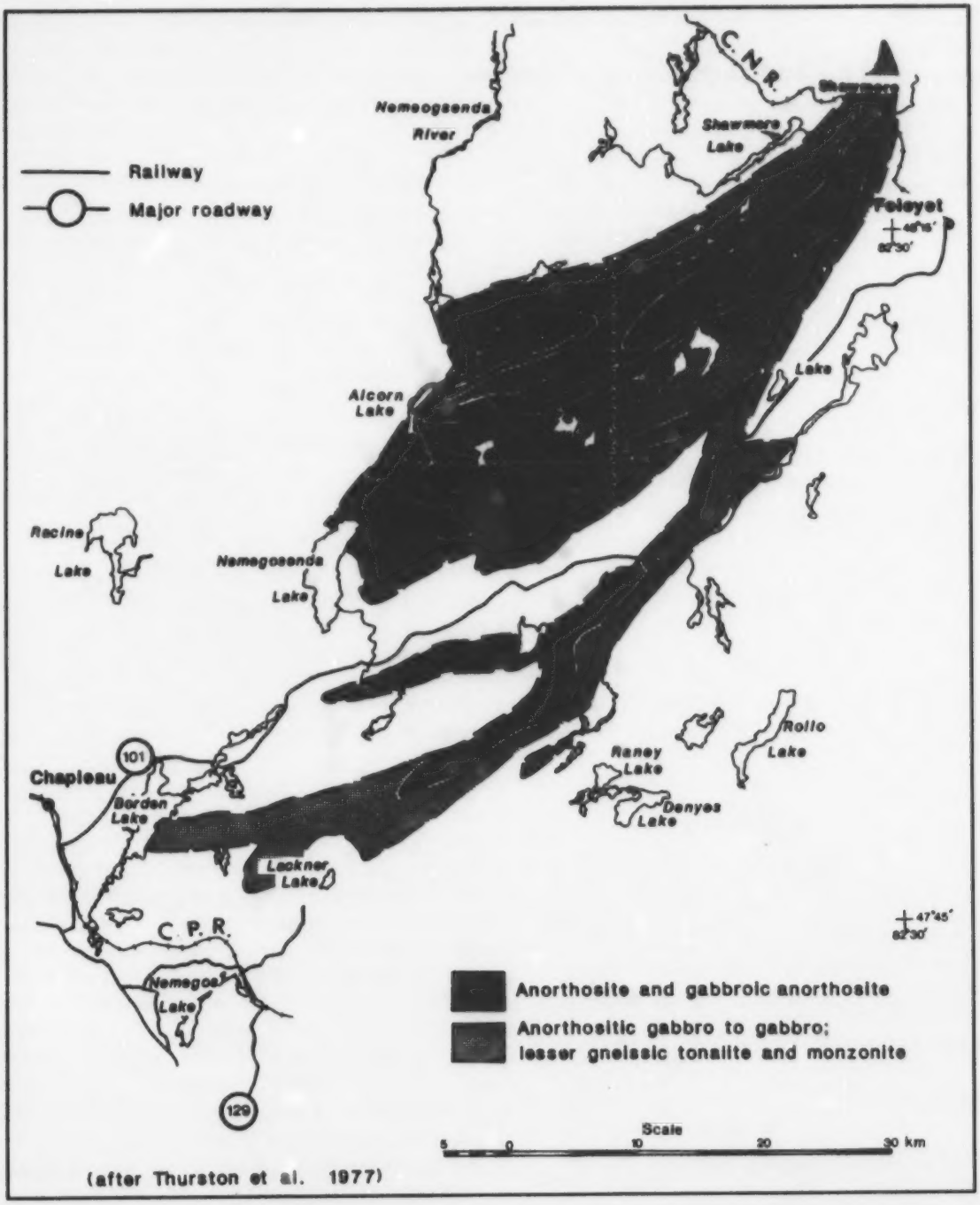


Figure 22. Shawmere Anorthosite Complex.

Exposure

Outcrop is limited, comprising approximately 10% of the areal extent of the complex. Exposure is relatively good in the vicinity of the Goose Range Fire Tower where rocks of the anorthosite core occur (Riccio 1979).

Geochemistry

Riccio (1979) gives major and selected trace element data on samples of several different rock types of the complex and surrounding rocks. Two analyses each of both anorthosite and leucogabbro are listed (Table 30).

Table 30
Chemistry of the Shawmere Complex

	1	2	3	4		5	6
SiO_2	47.70	47.60	47.70	49.00	SiO_2	49.50	50.50
Al_2O_3	31.10	32.10	28.50	26.50	TiO_2	0.11	0.19
Fe_2O_3	0.40	0.09	0.07	0.91	Al_2O_3	29.50	20.90
FeO	0.42	0.92	1.58	2.58	Fe_2O_3	0.17	1.50
MgO	0.50	0.53	2.82	4.33	FeO	1.12	3.04
CaO	15.00	15.40	14.60	14.00	MnO	0.02	0.10
Na_2O	2.43	2.58	1.96	2.00	MgO	1.38	9.23
K_2O	0.00	0.01	0.00	0.04	CaO	14.75	13.20
H_2O+	0.00	0.02	0.54	0.23	Na_2O	2.26	1.43
H_2O-	0.32	0.46	0.29	0.24	K_2O	0.17	0.12
CO_2	0.29	0.61	1.34	0.09	P_2O_5	0.01	0.18
TiO_2	0.07	0.09	0.07	0.13	Cr_2O_3	0.10	
MnO	0.01	0.02	0.03	0.05	H_2O+	0.72	0.59
P_2O_5	0.02	0.03	0.02	0.02	H_2O-	0.07	0.04
S	0.01	0.02	0.03	0.03	CO_2	0.26	0.16
TOTAL	98.30	100.50	99.50	100.10			
$CaO+Na_2O+K_2O$	17.43	17.99	16.56	16.04		17.18	14.75

	7	8	9	10	11	12
SiO_2	47.90	47.60	50.40	49.30	48.90	52.50
Al_2O_3	24.80	29.70	22.30	28.80	26.00	26.30
TiO_2	0.13	0.06	0.35	0.14	0.40	0.16
FeO	4.55	2.66	5.54	2.50	5.33	2.37
MgO	7.19	3.50	5.34	1.98	3.05	3.06
MnO	0.07	0.03	0.09	0.03	0.08	0.04
CaO	13.60	14.70	12.10	14.20	14.00	10.80
Na_2O	1.89	1.94	2.75	2.80	2.38	4.44
K_2O	0.17	0.09	0.27	0.11	0.16	0.19
TOTAL	100.30	100.30	99.10	99.90	100.30	99.90
$CaO+Na_2O+K_2O$	15.66	16.73	15.12	17.11	16.54	15.43

1[1] - Anorthosite
2[1] - Anorthosite
3[1] - Leucogabbro
4[1] - Leucogabbro
5[2] - Average of three anorthosites
6[2] - Anorthositic gabbro
7[3] - Gabbroic anorthosite, 80% plagioclase, 20% hornblende
8[3] - Anorthosite, 85% plagioclase, 12% hornblende, 3% garnet
9[3] - Gabbroic anorthosite, 80% plagioclase, 15% hornblende, orthopyroxenes, clinopyroxene, quartz.
10[3] - Gabbroic anorthosite, 85% plagioclase, 15% hornblende, biotite, garnet, opaques
11[3] - Gabbroic anorthosite, 80% plagioclase, 15% hornblende, 5% garnet, biotite, quartz, opaques
12[3] - Gabbroic anorthosite dike, 80% plagioclase, 10% hornblende, 5% garnet

[1]Riccio 1979
[2]Thurston et al. 1977
[3]Simmons et al. 1979

The anorthosite samples have Al_2O_3 values over 30% and the leucogabbro samples both contain over 25% Al_2O_3.

Thurston et al. (1977) give major element geochemistry for anorthosites and an anorthositic gabbro. An average of three anorthosite samples (Table 30) shows an Al_2O_3 content of 29.5 weight %.

Simmons et al. (1979) provide major and trace element data for gabbroic anorthosite samples from the Shawmere Complex (Table 30). All six samples are shown to have over 20% Al_2O_3.

Total alkali content is particularly high in the anorthosite samples which contain on average, over 17% $CaO+Na_2O+K_2O$. Alkali content is relatively high for all the Shawmere samples, averaging 16.38%.

Grenville Anorthosites

Northern Central Gneiss Belt

Anorthosites in the north half of the Central Gneiss belt share several similar traits. Most of these bodies are Early Proterozoic to Late Archean in age and intruded the Central Gneiss Belt after the peak of deformation in this region (Easton, personal communication). Cross cutting igneous relationships are evident. Many are troctolitic (i.e., olivine bearing) and they are commonly iron-titanium oxide-bearing (Lumbers, personal communication). The margins of these bodies are almost always recrystallized and gneissic in texture, with primary igneous mineralogy and textures preserved in the core of the intrusions. Anorthosites of this region are the Fall Lake, River Valley, Red Deer, St. Charles, Mercer and Eau Claire anorthosites. The Pickerel Complex occurs at the north-west end of the Central Gneiss Belt. It is mid-Proterozoic in age, and is situated in a different geological terrane from the other anorthosite occurrences (Easton, personal communication).

Fall Lake Anorthosite (31L/13)

The Fall Lake body is located in Flett and eastern Angus townships, 60 km due north of North Bay, and 30 km due east of McLarens Bay on Lake Timiskaming. The Ontario Northland Railway passes to the southwest of the body. There is a small dirt road passing within 500 m of the western flank of the body and exposures are accessible along shorelines of the several lakes (Figure 23). The town of Bushnell, on the Ontario Northland Railway, lies immediately south. The areal extent is just under 10 km^2.

Geology

The Fall Lake Anorthosite lies within the Central Gneiss Belt, just south of the Grenville Front. It consists of an oval body, which trends northeasterly and is approximately 3.2 km by 0.5 km. A larger, and possibly related body occurs immediately to the west. It is more mafic, primarily consisting of gabbro and diorite. The Fall Lake Anorthosite is not well studied, and details of mineralogy and textures are not available in the literature. All information on this body was derived from Lumbers (personal communication 1989; 1969, 1971a,b).

The Fall Lake Anorthosite is composed of anorthosite with minor gabbroic anorthosite and gneissic gabbroic anorthosite. The central part of the body is massive, medium- to coarse-grained with primary mineralogy and textures. The northern and southern extremities of the body are more mafic and are mapped as anorthosite with gabbroic anorthosite and minor metagabbro. Troctolitic anorthosite is present in the Fall Lake body. The margins are deformed, consisting of more mafic gabbroic anorthosite gneisses. The smaller anorthositic body is enclosed by gneissic tonalite, diorite and minor anorthosite which forms a narrow tail-like extension to the south.

Regional deformation has resulted in strongly deformed gneissic margins with a preserved, primary, igneous-textured anorthosite core. It is this core which represents the best target area since textures and compositions are likely the most homogeneous there.

Economic Aspects

There are iron-titanium occurrences in both the Fall Lake Anorthosite and adjacent mafic body (see Figure 23 for locations) (Lumbers 1971a,b). The larger, gabbroic body has been drilled in several places along a magnetic anomaly which extends from the north end of McDiarmid Lake south to Fanny Lake. Drill core data indicates magnetite, pyrite, garnet, hornblende, mica and minor silver mineralization (Flett Township, Geological Data Inventory Folio 199).

Titan Iron Mines Ltd. explored an iron-titanium-vanadium prospect located at the northeast tip of the smaller intrusion, in Angus Township (Ginn 1947). According to assessment file records there has been no significant exploration in the area recently (Ministry of Northern Development and Mines, Assessment Files Research Office).

Exposure

The absence of overburden in the immediate area of the intrusions (Lumbers 1971a,b) may be an indication of good exposure. Unfortunately, outcrop areas are not outlined and the extent of exposure cannot be estimated.

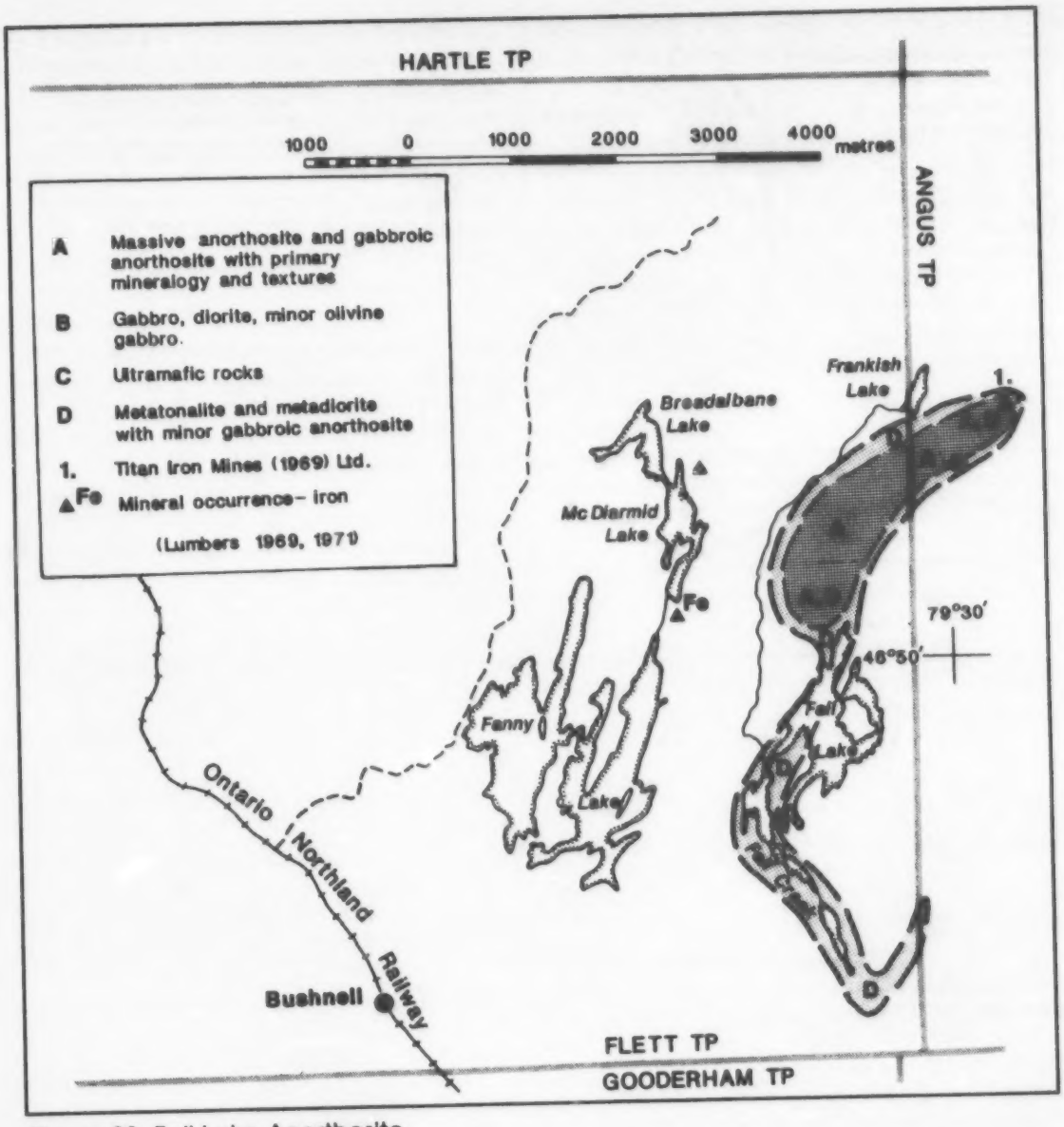


Figure 23. Fall Lake Anorthosite.

Geochemistry

Geochemistry for the Fall Lake bodies is not available.

River Valley Pluton (41I/09)

The River Valley intrusion is transected by Highway 805 and the Canadian National Railway, 50 km northeast of Sudbury. The body is spread across Janes, Henry, Dana, Crerar, McWilliams and Gibbons townships. The junction of Highway 805 and 539A, 1 km northeast of River Valley, marks the southern extent of the body. Minor roads branching from Highway 805 access the River Valley Pluton (Figure 24) which covers an area of approximately 100 km^2.

Geology

The River Valley Pluton is dated by Pb-Pb whole rock methods at 2560 ± 68 Ma (Ashwal and Wooden 1989; Easton 1991). The body lies immediately south of the Superior Province within the Grenville Front. It is extensive and has a very irregular shape, with finger-like extensions to the southwest and northeast.

Rock types consist of leuconorite, leucogabbro, anorthosite and minor ultramafics, diorite and tonalite

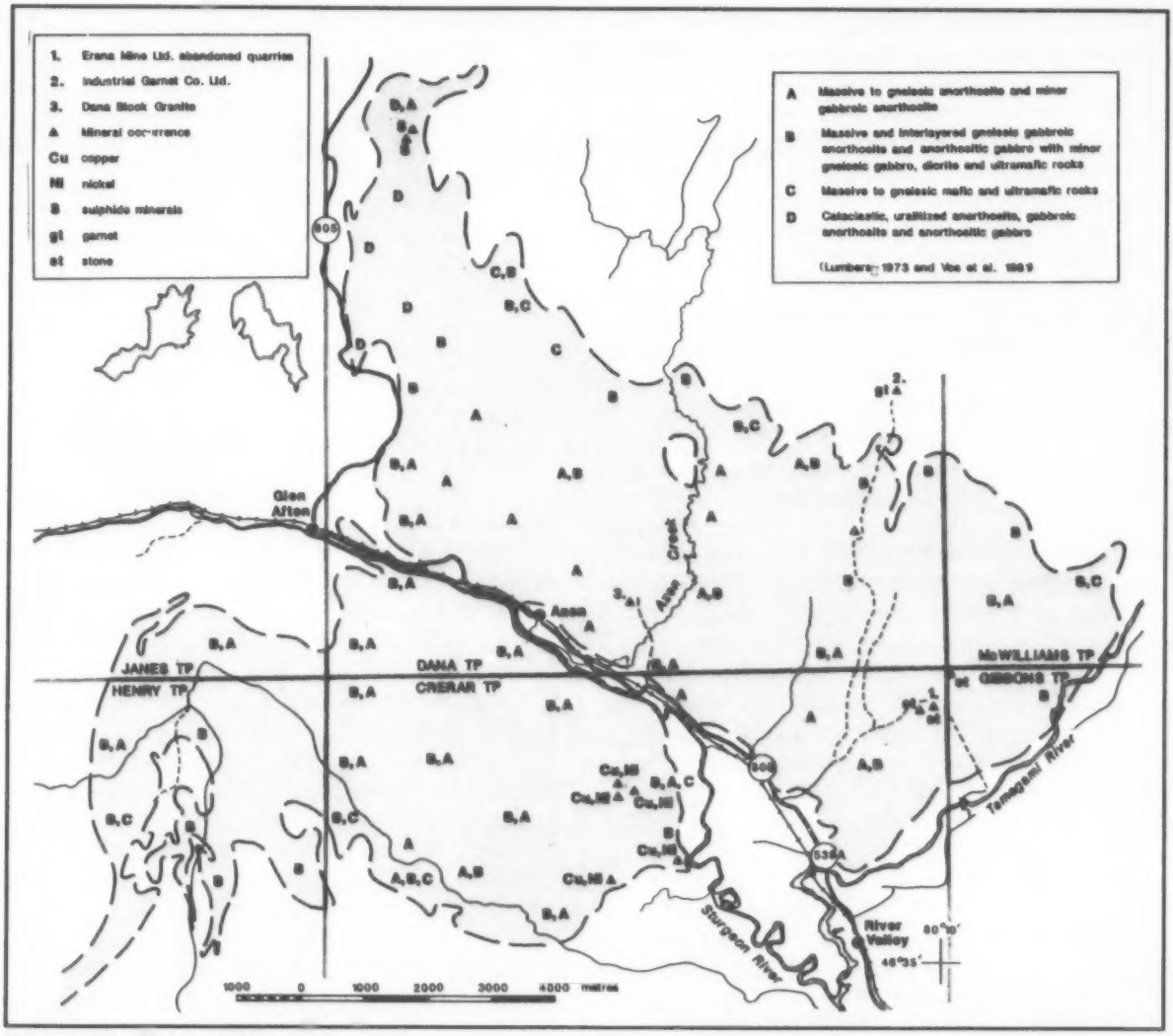

1. Erana Mine Ltd. abandoned quarries
2. Industrial Garnet Co. Ltd.
3. Dana Block Granite
▲ Mineral occurrence
Cu copper
Ni nickel
S sulphide minerals
gt garnet
st stone
A Massive to gneissic anorthosite and minor gabbroic anorthosite
B Massive and interlayered gneissic gabbroic anorthosite and anorthositic gabbro with minor gneissic gabbro, diorite and ultramafic rocks
C Massive to gneissic mafic and ultramafic rocks
D Cataclastic, unaltered anorthosite, gabbroic anorthosite and anorthositic gabbro
(Lumbers 1973 and Vos et al. 1981)
Glen Afton
Afton Creek
JANES TP
HENRY TP
DANA TP
CREAR TP
McWILLIAMS TP
GIBBONS TP
Temagami River
Sturgeon River
River Valley
905
535A
1000 0 1000 2000 3000 4000 metres

Figure 24. River Valley Pluton.

(Lumbers 1971). The western lobe, in northern Henry Township is predominantly gabbroic anorthosite, characteristically gneissic and generally more mafic in composition (Lumbers 1971). The rest of the body consists of massive to gneissic, medium- to coarse-grained mixed rock types, with discernible patches of predominantly anorthosite (Figure 24).

The River Valley Pluton is variably deformed and metamorphosed, with the most intense effects at the margins of the body. Metamorphic grade intensifies from greenschist in the west to mid- to upper-amphibolite facies in the east. Textures vary from medium- to coarse-grained and gneissic to massive, with augen gneisses occurring locally. Textural and compositional variations, including primary igneous layering are transitional and occur at outcrop scale (Lumbers 1971; Dressler 1979).

Calcic plagioclase and hornblende are the major minerals, with minor garnet, epidote, biotite, chlorite, sphene, and quartz (Ashwal and Wooden 1989). Ilmenomagnetite inclusions in the plagioclase produce the black anorthosite which is common to the quarries in the River Valley anorthosite. Plagioclase in the black anorthosite quarries is bytownite in composition (An_{65-85}) (Vos et al. 1981) and the recrystallized plagioclase in Janes Township has compositions ranging from An_{50-78} (Dressler 1979). Recrystallized anorthosite in Janes Township is described by Dressler (1979) as fine grained and granular, containing some larger (1 cm diameter) plagioclase grains and hornblende aggregates. Garnet occurs locally in the matrix. Unaltered, clear, recrystallized plagioclase grains occasionally overgrow relict, altered porphyroclasts (Dressler

1979). The relict plagioclase commonly contains epidote (Dressler 1979). Mafic mineralogy is variable, with hypersthene, augite and chlorite present in the old Dana Quarry, uralite plus biotite in the Erana quarries, and olivine plus augite in the River Valley Stone Manufacturing Co. quarry (see Figure 24 for locations of quarries) (Vos et al. 1981). Pyroxene grains are often uralitized, with coronas of fibrous amphibole, particularly in the black anorthosite (Vos et al. 1981).

Economic Aspects

The River Valley anorthosite is quarried for building stone in several localities (Figure 24). The most recent activity appears to have been the 1980 purchase by Mid Canada Shield Ltd. (Sudbury) of the River Valley Stone Manufacturing Co. quarry (Ontario Geological Survey 1984). Garnet occurrences just north of the pluton have been developed and some garnet was extracted for use as abrasives (Mineral Deposits Inventory Records). Sulphide mineral occurrences are noted on Lumbers' map (1973b) in the northern extension of the body and several copper-nickel occurrences as disseminated pyrite and chalcopyrite occur in gabbro just west of River Valley. In the mid-60s, Falconbridge Nickel Mines Ltd. (Shklanka 1969) drilled and trenched these occurrences.

Exposure

The River Valley area was mapped by Lumbers in 1973 (1973b). Although individual outcrops are not indicated on the map, unconsolidated Quaternary deposits are shown to cover only small areas and it is therefore assumed that exposure is relatively good. The quarries on the deposit also presumably provide good exposure. Mapping by Dressler (1979) covers the far northwest corner of the River Valley Pluton (southern Janes Township) where exposure is estimated to be 15%.

Geochemistry

Dressler (1979) (Table 31) provides a table of modal analyses of several rock types in the River Valley Pluton. Plagioclase compositions and proportions vary notably among the samples. One chemical analysis is given for a sample of unknown lithology. The sample contains 22.8 weight % Al_2O_3 and has a total alkali content of 15.74%.

Red Deer Anorthosite (41I/07)

The Red Deer Anorthosite is situated in Awrey, Dry-

Table 31
Chemistry and Modal Analysis for the River Valley Pluton

Sample	9C10A
wt. %	
SiO2	49.30
Al203	22.80
Fe2O3	2.10
FeO	3.17
MgO	4.15
CaO	12.20
Na2O	2.68
K2O	0.86
TiO2	0.26
MnO	0.12
P2O5	0.06
H2O+	1.57
H2O-	0.22
S	0.01
TOTAL	99.60
CaO+Na2O+K2O	15.74

Sample	9C10B	10D3B	10D3C	10D3B
Modes				
quartz	2.0	0.3		3.0
plagioclase	41.4	81.9	72.2	44.2
clinopyroxene	1.2	-	-	-
hornblende	-	14.0	18.2	24.4
tremolite	6.0	-	-	-
biotite	-	0.3	0.2	7.2
sphene	-	tr.	-	-
opaques	0.1	tr.	tr.	0.4
epidote	41.9	3.2	9.4	20.8
chlorite	5.6	0.3	-	-
plagioclase (plagioclase, epidote, chlorite sericite, pseudomorphing plagioclase)	88.9	84.8	81.6	65.0
plagioclase compostion (Anx)	n.d.	78+/.5	n.d.	50+/.5

9C10B: deformed anorthosite
10D3B: massive gabbroic anorthosite
10D3C: gneissic gabbroic anorthosite
10D3B: gneissic anorthositic gabbro

(Dressler 1979)

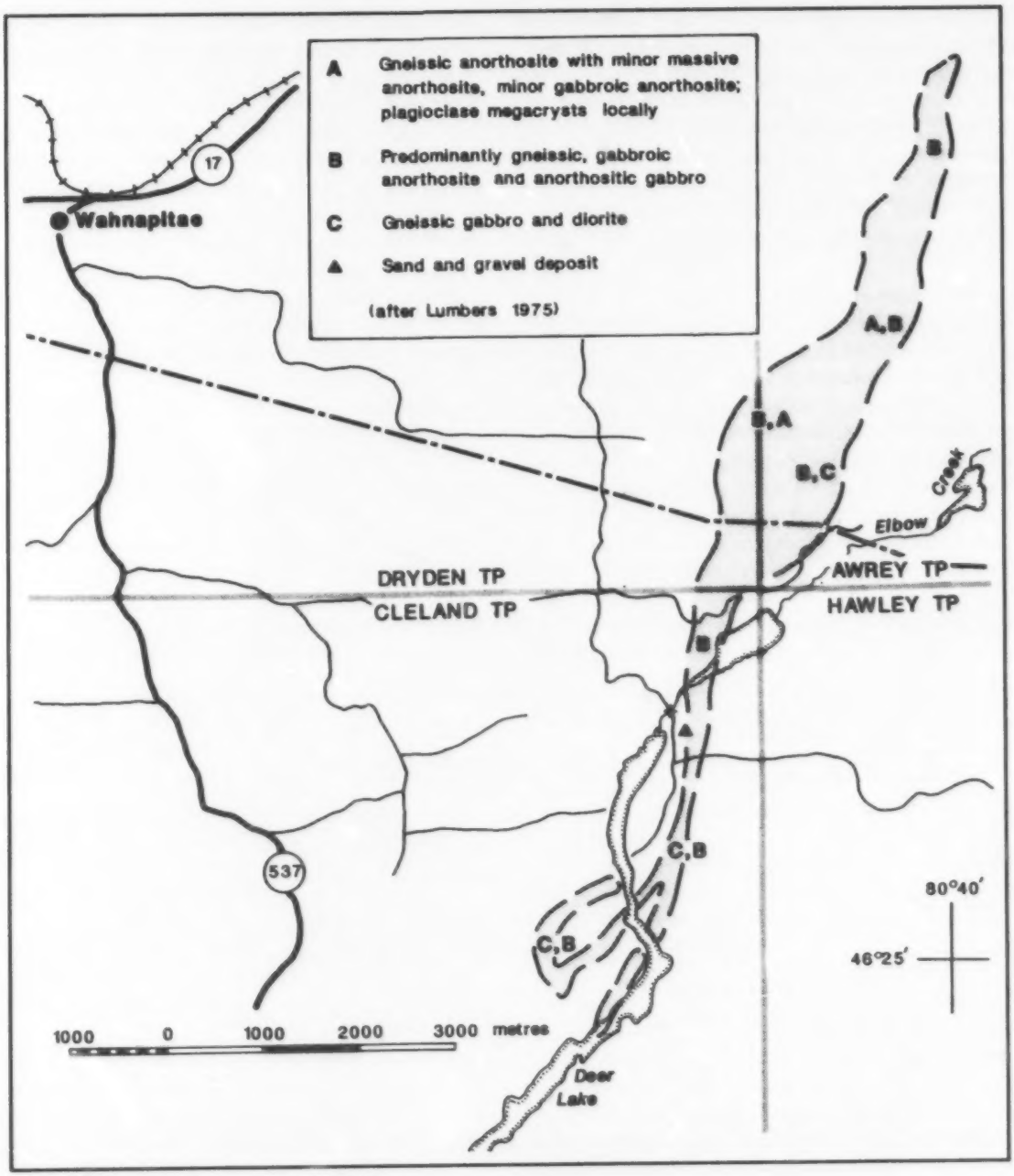


Figure 25. Red Deer Anorthosite.

den and Cleland townships, approximately 20 km east of Sudbury. Access is afforded by Highway 17 east to Wahnapitae, and southeast on Highway 537 (Figure 25). The Red Deer Anorthosite covers an area of approximately 4 km^2.

Geology

The Red Deer body is a long, northeast-trending unit, lying just south of the Grenville Front. The proximity of the Red Deer Anorthosite to the River Valley Pluton and the Grenville Front has led to suggestions of a genetic link between the two bodies (Easton 1991). Although it has not been dated, the Red Deer Anorthosite is probably Early Proterozoic to Late Archean in age, as is the River Valley Anorthosite (Easton, personal communication). The Red Deer Anorthosite has not been studied in detail. Reconnaissance studies by Lumbers (1975) describe the

general geology of the Red Deer body (as with the Pickerel Complex, Mercer and St. Charles anorthosites).

In general terms, Lumbers (1975) describes anorthositic rocks of the Burwash area as medium- to coarse-grained, massive to gneissic rocks with primary igneous layering present in the massive zones. The margins are deformed and gneissic whereas the cores preserve original textures and mineralogy (Lumbers, personal communication). Plagioclase commonly occurs as coarse phenocrysts up to 20 cm in the core areas (Lumbers 1975). These large relict grains are grey and contain inclusions of iron-titanium oxide minerals (Lumbers 1975). Plagioclase compositions determined for anorthosites and anorthositic rocks average An_{50}, labradorite. Other minerals in order of abundance are hornblende (ferrohastingsite), biotite, quartz, K-feldspar, apatite, sphene, epidote, allanite, carbonate and scapolite. Zircon is reported as an abundant accessory mineral, characteristic of the anorthosite suite.

More specifically, the Red Deer body consists of gneissic, anorthositic gabbro and gabbroic anorthosite with minor metagabbro and metadiorite along the eastern and southern margins (Lumbers 1975). Primary features such as relict igneous layering occur in the more gabbroic margins. The central portions of the body are massive anorthosite with primary megacrystic textures.

Economic Aspects

There are no known mineral occurrences associated with this intrusion except for the presence of locally disseminated, titaniferous magnetite (Lumbers 1972a) which is apparently characteristic of all anorthosite bodies situated immediately south of the Grenville Front (River Valley, Eau Claire, Fall Lake).

Exposure

The extent of exposure is not described by Lumbers (1972a; 1975), and it is unknown if the body is well exposed.

Geochemistry

Lumbers (1975) gives one analysis from the Red Deer body, a gneissic anorthositic gabbro. Major and selected trace elements plus C.I.P.W. norms for the sample are listed in Table 32. Considering the mineralogy of a gabbro, the Al_2O_3 content is high at 22.2%. The total alkali content for the sample is 15.56%. It is likely that samples of the massive anorthosite in the centre of the body would be higher in alumina and alkalies.

PICKEREL COMPLEX (41H/15, 41I/02)

The Pickerel Complex is a folded sheet, the arms of which straddle the Pickerel River inlet from Georgian Bay, (around 4 km west of Key Harbour, see Figure 26). The hinge of the fold lies on the north side of the Pickerel River, in the southern end of Allen Town-

Table 32
Chemistry of the Red Deer Anorthosite

Major elements:		Trace elements:		C.I.P.W. Norms:	
	wt.%		p.p.m.		%
SiO_2	51.40	Ag	2	Quartz	6.8
Al_2O_3	22.20	As	2	Orthoclase	2.2
Fe_2O_3	1.34	Ba	-	Albite	17.0
FeO	5.16	Be	-	Anorthite	51.1
MgO	2.25	Co	40	Corundum	-
CaO	13.10	Cr	150	Olivine	-
Na_2O	2.02	Cu	140	Hypersthe	8.3
K_2O	0.44	Ga	15	Diopside	11.0
H_2O+	0.64	Ni	110	Acmite	-
H_2O-	0.24	Pb	10	Magnetite	1.9
CO_2	0.18	Sb	1	Hematite	-
TiO_2	0.26	Sc	30	Ilmenite	0.6
P_2O_5	0.01	Sr	300	Apatite	-
S	0.01	V	150	Calcite	0.5
MnO	0.13	Zn	50	H_2O	0.6
Total	99.40	Y, Zr	-	Total	100.0
$CaO+Na_2O+K_2O$	15.56				

A gneissic, anorthositic gabbro from the Red Deer Anorthosite in Awrey Twp. (Lumbers 1975).

ship. The two anorthositic units of the complex, have an areal extent of approximately 5 km^2.

Geology

The body occurs at the west edge of the Central Gneiss Belt, in the Grenville Province. Although it has not been dated, the body is probably Middle Proterozoic, occurring in a different geologic terrane than other anorthosites of this belt.

The Pickerel Complex has not been studied in detail. Reconnaissance studies by Lumbers (1975) describe the general geology of the northern third of the Pickerel Complex and the general outline of the southern two thirds was mapped by Quirke (1929).

The northern third is dominated by anorthosite with gabbroic rocks concentrated along the western margin (Lumbers 1972a). Anorthositic gabbro and gabbroic anorthosite are associated with the anorthosite locally (Lumbers 1972a). Most of the rocks of the Pickerel Complex are strongly gneissic, especially at the margins. However, massive and slightly foliated anorthosites are reported in the fold hinge, near the road to Hartley Bay (Lumbers 1972a). Inclusions of metasediments are common throughout the complex, and are especially abundant along the eastern margin (Lumbers 1972a).

Details of petrography for the Pickerel Complex are sparse. Modal analysis of a "diorite" from the Pickerel River complex revealed the following mineralogy: 81.8% plagioclase, 11.3% biotite, 4.05% garnet, 2.85% amphibole, less than 1% magnetite + apatite (Quirke 1929). This sample was collected near the Canadian National Railway bridge over French River (Quirke 1929). Plagioclase compositions are not given.

Economic Aspects

Examination of assessment files (Assessment Files Research Office, Toronto) and the mineral deposit inventory records (Toronto) show that there are no known mineral occurrences in the Pickerel Complex.

Exposure

Sections across the complex are well exposed along the Canadian National Railway, the road leading to Hartley Bay and along the shore of both the French and Pickerel Rivers (Lumbers 1972).

Geochemistry

Four analyses are listed in Table 33 including a gneissic anorthosite sample (Lumbers 1975), a gneissic gabbroic anorthosite and gneissic anorthosite (Maxwell 1965) and the diorite sample referred to above from Quirke (1929). Lumbers (1975) lists eight analyses of rocks from the Pickerel Complex, Allen

Table 33
Chemistry of the Pickerel Complex

	A	B	C	D
Major elements: wt.%				
SiO_2	55.20	55.20	55.13	56.18
Al_2O_3	23.90	23.13	23.76	23.26
Fe_2O_3	1.28	1.09	0.57	.81
FeO	2.25	2.69	2.46	2.27
MgO	2.44	3.13	2.54	1.59
CaO	8.35	9.47	9.00	8.55
Na_2O	3.66	3.42	3.59	4.61
K_2O	1.77	1.18	1.37	1.59
H_2O+	0.49	0.36	0.69	.56
H_2O-	0.31	0.04	0.06	.01
CO_2	0.12	0.09	0.13	
TiO_2	0.29	0.21	0.27	.27
P_2O_5	0.04	0.18	0.32	.20
S	0.01	0.15	-	-
MnO	0.05	tr.	-	.05
Total	100.20	100.34	99.89	100.02
Trace elements: p.p.m.				
Ag	1	-	-	-
As	1	-	-	-
Ba	600	-	-	-
Be	-	-	-	-
Co	20	-	-	-
Cr	40	-	-	-
Cu	20	-	-	-
Ga	20	-	-	-
Ni	70	-	-	-
Pb	10	-	-	-
Sb	1	-		-
Sc	-	-	-	-
Sr	600	-	-	-
V	20	-	-	-
Y	20	-	-	-
Zn	60	-	-	-
Zr	100	-	-	-
C.I.P.W. Norms: %				
Quartz	4.8	5.3	4.4	-
Orthoclase	7.2	8.3	10.7	-
Albite	29.0	30.4	31.0	-
Anorthite	43.8	42.4	41.6	-
Corundum	0.8	0.7	-	
Olivine	-			
Hypersthene	10.2	9.7	8.6	-
Diopside	2.5	-		
Acmite	-			
Magnetite	1.6	0.9	1.9	-
Hematite	-			
Ilmenite	0.5	0.6	0.6	-
Apatite	0.7	-		
Calcite	0.2	-		
H_2O	0.4	0.7	0.5	-

A : Gneissic anorthosite, "transitional into diorite" (Lumbers 1975), Allen Township.
B : Gneissic gabbroic anorthosite, Allen Township. (Maxwell 1965)
C : Gneissic anorthosite, Allen Township. (Maxwell 1965)
D : Diorite, from near C.N.R. bridge over Pickerel River (Quirke 1929)

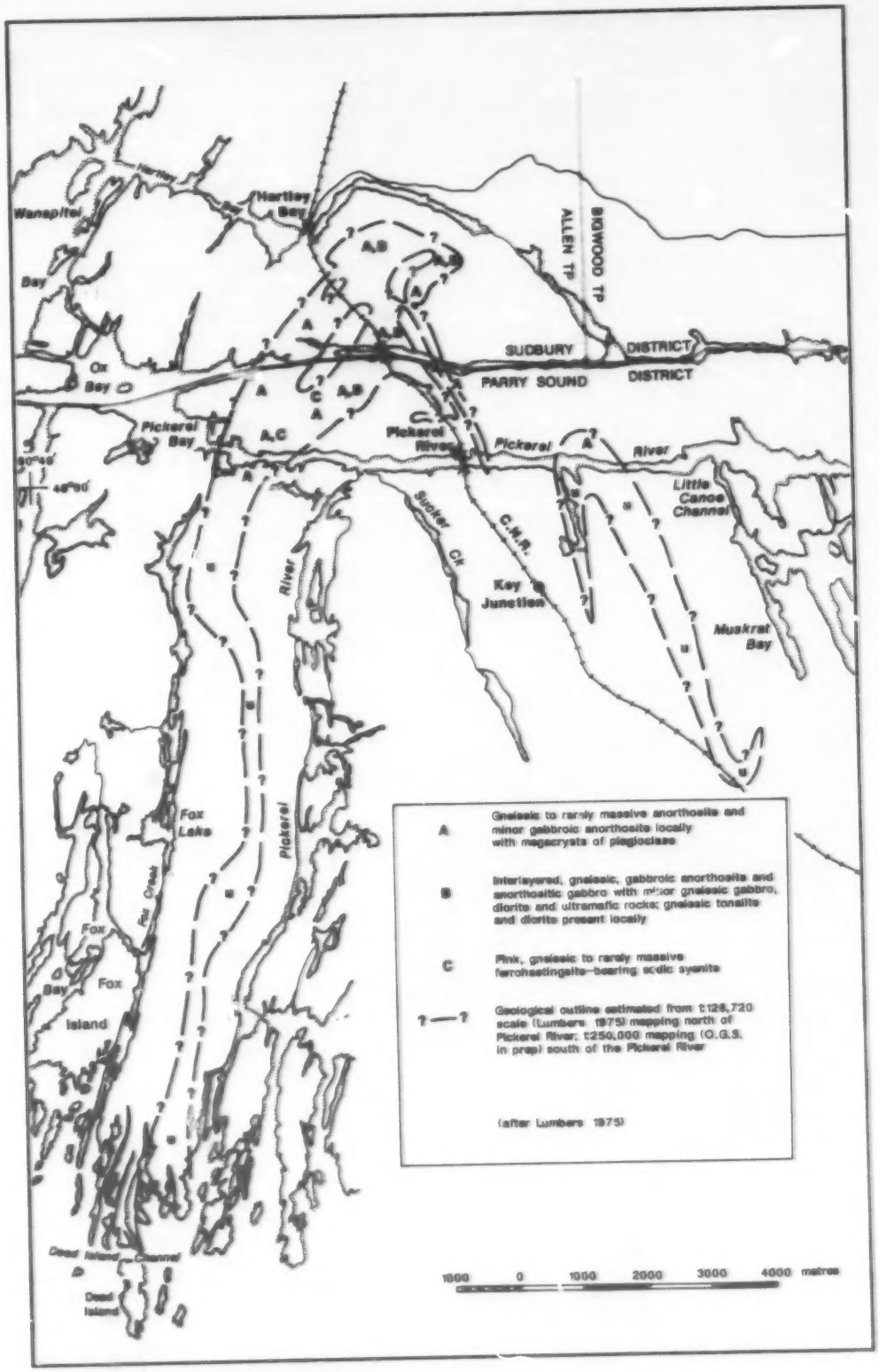


Figure 26. Pickerel Complex.

Township, including two anorthositic samples, plus tonalite, monzonite and syenite samples. Anorthositic samples show Al_2O_3 values around 23%. The average total alkali content for analyses listed here is 13.93% which is distinctly lower than the total alkali content of other Grenville anorthosites.

St. Charles Anorthosite (41I/08)

The St. Charles Anorthosite is located 50 km east of Sudbury in Casimir Township. The northwest end of the body is accessible by Highway 535, south of St. Charles, and by county road north from the town of Casimir. The body covers an area of approximately 3 km^2.

Geology

The St. Charles Anorthosite (Figure 27) is a cigar shaped, northwest trending body, 11 km by 0.8 km. The shape and steep dips suggest that the body is a sill (Rousell 1978). Compositions range from gabbro through to anorthosite with anorthositic rock types dominating. Both massive and foliated anorthosites occur throughout but the more deformed rocks are prevalent at the margins (Lumbers 1975). Gabbro and gabbroic anorthosite are interlayered with the anorthosite where the body is foliated (Rousell 1978). Large (up to 30 cm by 20 cm) plagioclase phenocrysts occur in both the massive and foliated anorthosite. Plagioclase compositions range from andesine to labradorite (Rousell 1978). Mafic minerals include

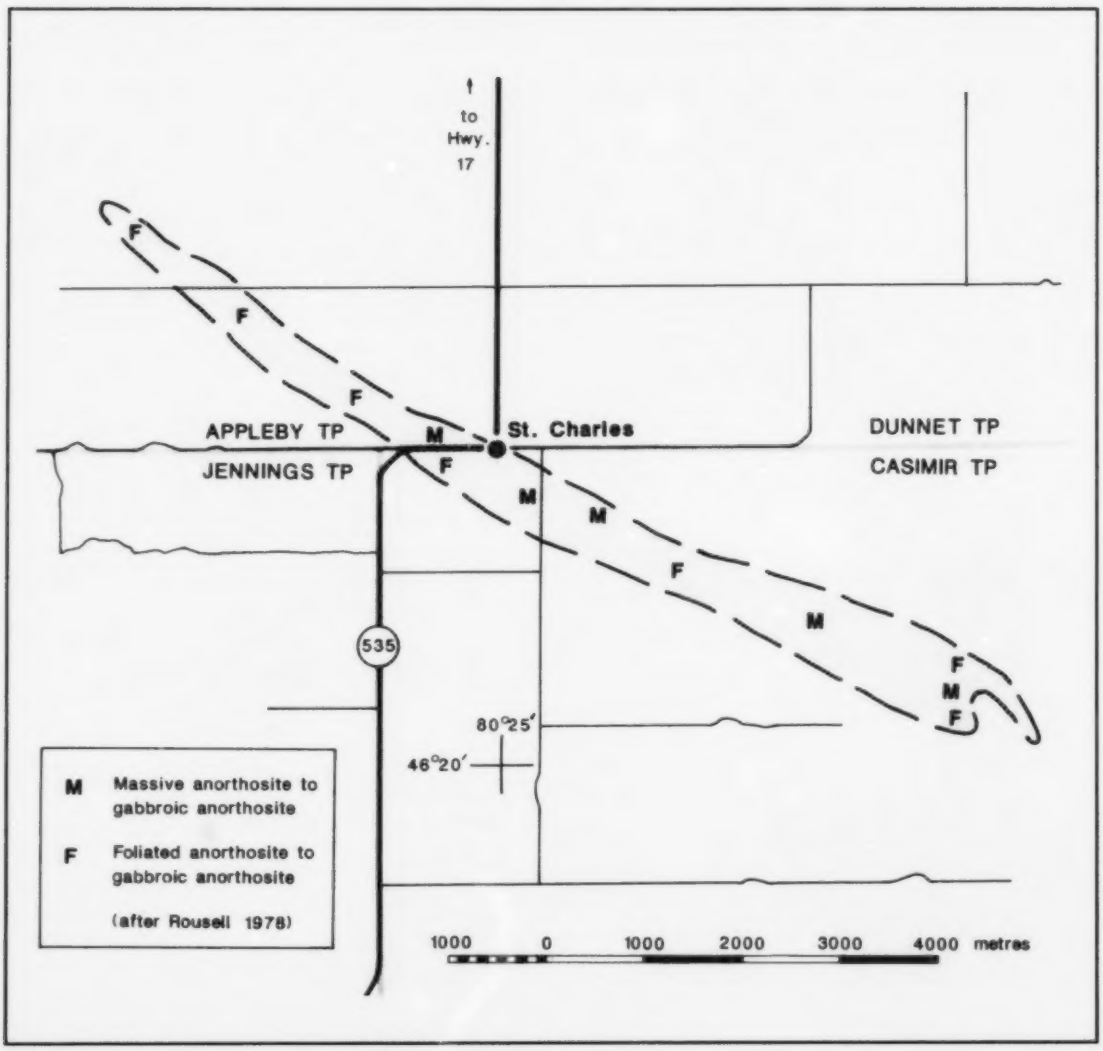


Figure 27. St. Charles Lake Anorthosite.

hornblende and biotite which occur as coarse (3 cm diameter) subophitic masses and as fine, interstitial grains. Mafic clots are locally stretched (Rousell 1978) into narrow streaks, forming a weakly banded, gneissic texture. Garnet, chlorite, sericite and epidote are also common but not abundant (Rousell 1978). Modal analyses for representative samples from all rock types (Rousell 1978) are listed in Table 34.

The St. Charles Anorthosite is crosscut by minor syenitic and enderbitic dikes (Lumbers 1975) and areas of 1 to 3 m joint spacing have been noted.

Economic Aspects

Recent activity (Spring 1989) by Norgranite Co.

Table 34
Chemistry of the St. Charles Anorthosite

	1	2	3	4	5	6	7	8	9
SiO_2	50.19	53.28	51.51	51.40	52.77	52.00	51.98	50.40	53.12
Al_2O_3	23.78	24.38	25.05	25.38	25.68	25.41	25.32	23.84	24.72
Fe_2O_3	6.78	3.85	4.31	4.15	3.32	3.13	3.56	6.39	5.43
MgO	2.98	1.46	1.81	1.96	1.53	1.31	1.75	2.37	2.07
CaO	10.23	10.05	10.33	10.79	10.68	10.61	10.34	10.38	7.14
Na_2O	3.66	4.10	4.00	3.84	4.39	4.13	4.36	3.79	4.38
K_2O	0.68	0.82	0.78	0.71	0.63	0.53	0.73	0.82	0.72
H_2O	0.70	0.75	0.96	0.64	0.87	0.64	0.75	0.64	0.75
TiO_2	0.90	0.55	0.68	0.57	0.49	0.44	0.34	0.85	0.79
P_2O_5	0.15	0.22	0.13	0.10	0.10	0.10	0.08	0.20	0.14
S	0.02	0.00	0.02	0.00	0.01	0.01	0.01	0.00	0.01
MnO	0.10	0.05	0.06	0.05	0.04	0.04	0.04	0.08	0.07
$CaO+Na_2O+K_2O$	14.57	14.97	15.11	15.34	15.70	15.27	15.43	14.99	12.24
TOTAL	100.17	99.51	99.64	99.59	100.51	98.35	99.26	99.76	99.24
TRACES (ppm):									
Cu	19	7	22	9	9	14	28	10	20
Zn	40	27	35	29	22	20	40	47	40
Co	45	40	55	35	35	55	30	38	40
Ni	40	15	30	40	19	32	8.5	30	28
Cr	32	11	33	25	27	23	50	55	
MODES:									
Plagioclase	62.6	78.4	82.4	82.6	81.2	86.4	80.2	80.6	79.2
Hornblende	27.8	19.2	10.2	14.8	16.0	10.6	10.8	15.6	15.8
Biotite	3.8	1.0	0.8	1.8	1.0	2.6	1.0	1.2	2.4
Garnet	1.6	0.2	8.0			tr	0.4	tr	
Opaques	2.0	0.2	0.2	2.0		0.2	tr	tr	tr
Sericite	1.8	0.2	1.8	0.4		2.8	1.2	1.0	
Epidote	0.2	0.6	2.6	tr	tr	1.8	0.4	0.6	
Chlorite	0.2	tr	2.0	0.2	0.4	2.8	0.2	0.6	
Allanite	tr	tr				0.4			
Apatite	0.4	0.2	tr	0.4		0.2	0.2	0.4	tr
Quartz	tr					tr	tr	0.0	
Spinel						tr			

Sample 1 is a foliated gabbro.
Samples 2 and 3 are foliated, gabbroic anorthosite.
Samples 4,5,6 and 7 are massive, gabbroic anorthosite.
Samples 8 and 9 are foliated, gabbroic anorthosite.

(Rousell 1978)

Ltd. has concentrated on evaluating building stone potential of the St. Charles Anorthosite. Areas of 1 to 3 m joint spacing, with even colour and texture favourably describe the building stone potential of the St. Charles Anorthosite (Assessment Files Research Office File 2.12358).

Exposure

The St. Charles Anorthosite sill is well exposed over its entire length. Outcrops and lithological distributions are clearly represented on Rousell's (1978) map.

Geochemistry

Geochemistry is listed for nine samples in Table 34 (Rousell 1975). Enrichments of Fe_2O_3 and MgO at the margins of the sill have been noted (Rousell 1978). Al_2O_3 content is consistently around 24 weight % and total alkali content averages 14.85 weight %.

Mercer Anorthosite (41I/01)

The Mercer Anorthosite is located in the northwestern corner of Falconer Township, 6 km east of Monetville. The areal extent of the body is estimated at 4 km^2. The body is accessible by numerous roads which branch eastward from Highway 64.

Geology

The Mercer Anorthosite (Figure 28) lies in the Central Gneiss Belt of the Grenville Province. It is a very irregularly shaped body with narrow protrusions extending north and south into the surrounding granites. Although it has not been dated, the body is probably Early Proterozoic to Late Archean in age (Easton personal communication), as are the other anorthosite bodies along the southern margin of the Grenville Front (Lumbers 1975).

The Mercer Anorthosite has not been studied in detail although reconnaissance studies by Lumbers (1972; 1975) describe the Mercer body relative to the other anorthosite suite rocks of the Burwash area, namely the Pickerel Complex, Red Deer, and St. Charles anorthosites. In general, the anorthosites of the Burwash area are medium- to coarse-grained gabbroic anorthosites. Plagioclase is characteristically labradorite, averaging An_{50} (Lumbers 1975). Other minerals common to the anorthosite suite of the Burwash area are, in order of abundance, hornblende (ferrohastingsite), biotite, quartz, K-feldspar, apatite, sphene, epidote, allanite, carbonate and scapolite (Lumbers 1975). Zircon is an abundant accessory mineral (Lumbers 1975).

The Mercer intrusion, specifically, consists of predominantly gneissic anorthosite, and minor gabbroic anorthosite. Gneissic tonalite and diorite occur locally, particularly at the margins and in the protruding southern arm crossing Marshall Lake where gneissic diorite and tonalite predominate. Lumbers (1972) describes the tonalite and diorite of this locality as grading into anorthosite.

The rocks are less intensely deformed towards the centre of the body, where massive to slightly foliated anorthosite is reported (Lumbers 1972). The small area of massive anorthosite contains relic plagioclase crystals up to 10 cm in diameter which commonly contain inclusions of iron-titanium oxide minerals (Lumbers 1975). Localized patches of biotite occur in the gabbroic anorthosite and alteration of plagioclase to scapolite is common (Lumbers 1972). Red staining by hematite alteration occurs locally, along closely spaced fractures (Lumbers 1972). This addition of iron to the bulk chemistry may seriously affect feldspar potential.

Granite inclusions are present within a few metres or less of the margin and the Mercer body is crosscut by a few tonalite and quartz syenite dikes.

Economic Aspects

There are no mineral occurrences indicated on Lumbers' map, (1975) and there is no record of mining activity in the area of the Mercer intrusion (Assessment Files Research Office).

Exposure

The Mercer Anorthosite is well exposed particularly at the contacts with the surrounding granite (Lumbers 1972).

Geochemistry

Table 35 shows the single analysis given for the Mercer Anorthosite by Lumbers (1975). Al_2O_3 is 24.2% and the total alkali content is 14.56%.

Eau Claire Anorthosite (31L/SE)

The Eau Claire Anorthosite occurs (Figure 29) south of Mattawa in Renfrew County. The body extends from Calvin Township southeast through Papineau, Lauder and Boyd townships. The main body is accessible via Highway 630, south from Highway 17. Smaller access roads are indicated on the detailed map. The Eau Claire Anorthosite has not been studied in detail and there is no geochemistry available. However, the 30 km^2 body may possess substantial resource potential.

Geology

Brief reports by Lumbers (1972b; 1973a; 1974) describe the Eau Claire bodies as a "complex anorthositic intrusion", composed of anorthosite and

gabbroic anorthosite for the most part. The Eau Claire body is described as sheet-like (Lumbers 1972b). There is a wider, rounded mass in Calvin Township which narrows progressively toward the south where three elongate lobes pinch out. Two worm-shaped bodies, only 200 to 400 m in width extend further south.

Primary igneous layering and massive textures are present, however gneissic anorthosite predominates

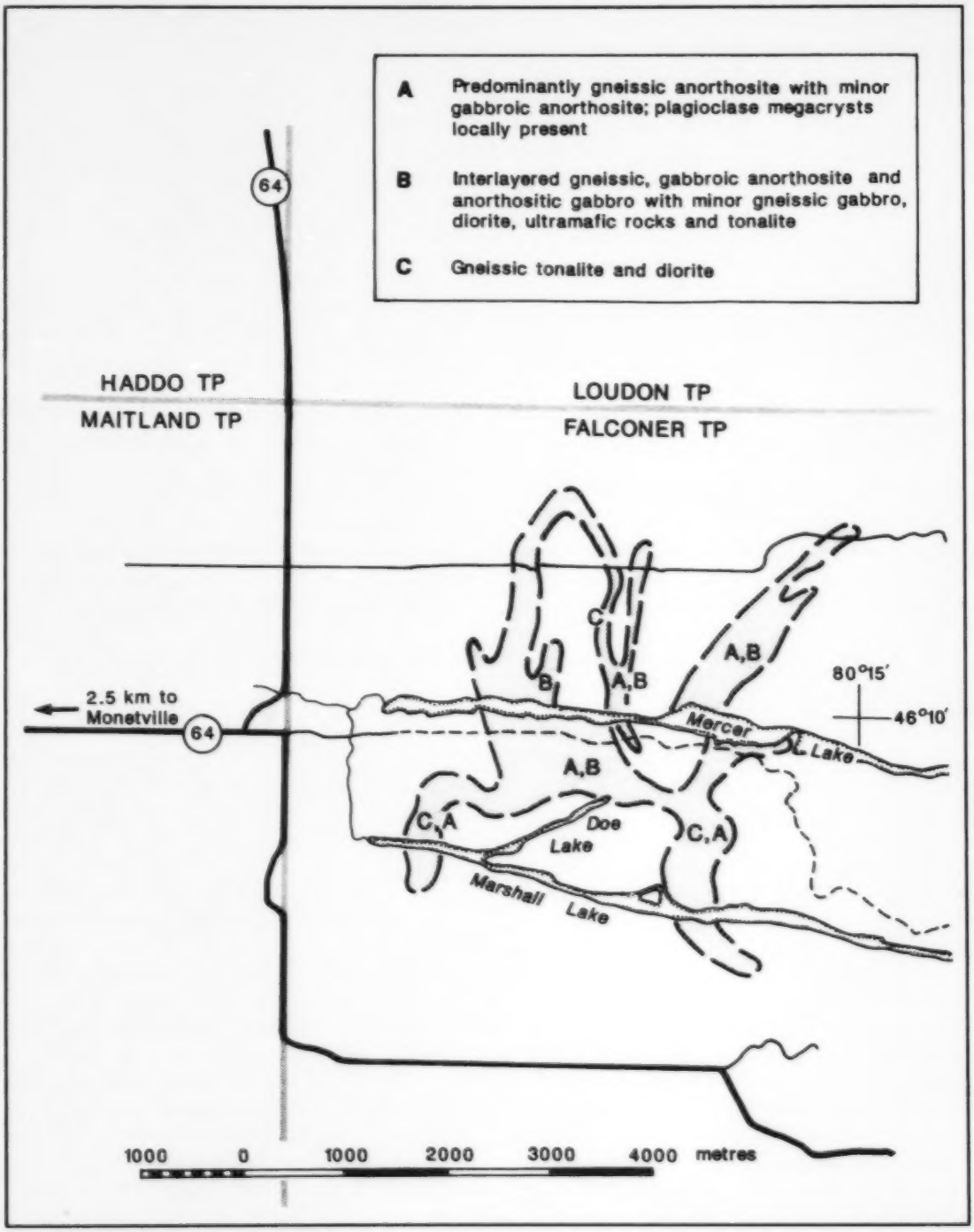


Figure 28. Mercer Anorthosite.

Table 35
Mercer Anorthosite

Major elements: wt.%		Trace elements: p.p.m.		C.I.P.W. Norms: %	
SiO_2	53.10				
Al_2O_3	24.20	Ag	-	Quartz	4.8
Fe_2O_3	0.86	As	5	Orthoclase	9.4
FeO	1.93	Ba	800	Albite	33.8
MgO	1.30	Be	-	Anorthite	43.0
CaO	9.00	Co	6	Corundum	-
Na_2O	4.00	Cr	40	Olivine	-
K_2O	1.56	Cu	4	Hypersthene	5.1
H_2O+	1.15	Ga	20	Diopside	-
H_2O-	0.17	Ni	30	Acmite	-
CO_2	0.13	Pb	30	Magnetite	1.4
TiO_2	0.46	Sb	4	Hematite	-
P_2O_5	0.12	Sc	20	Ilmenite	0.9
S	0.08	Sr	600	Apatite	0.3
MnO	0.06	V	50	Calcite	0.20
Total	98.10	Zn	40	H_2O	1.10
$CaO+Na_2O+K_2O$	14.56	Y, Zr	-	Total	100.00

A gneissic anorthosite sample from the Mercer Anorthosite, Falconer Twp. (Lumbers, 1975).)

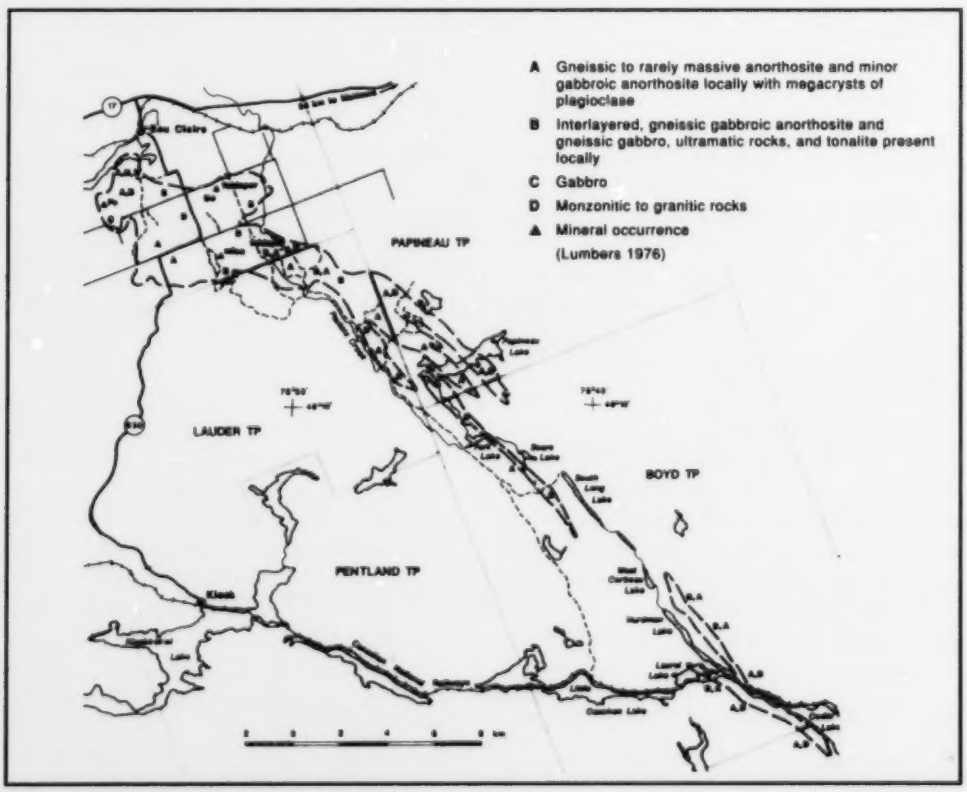

A Gneissic to rarely massive anorthosite and minor gabbroic anorthosite locally with megacrysts of plagioclase
B Interlayered, gneissic gabbroic anorthosite and gneissic gabbro, ultramatic rocks, and tonalite present locally
C Gabbro
D Monzonitic to granitic rocks
▲ Mineral occurrence
(Lumbers 1976)
PAPINEAU TP
LAUDER TP
PENTLAND TP
BOYD TP

Figure 29. Eau Claire Anorthosite.

(Lumbers 1972b). Lumbers (personal communication)has determined that the Eau Claire Anorthosite is troctolitic, i.e., olivine-bearing and is similar to the River Valley body in many respects. Parts of the body are recrystallized, pure, massive anorthosite but most of the body consists of mixed anorthosite and gabbro, often olivine-bearing and commonly gneissic, particularly at the margins.

These rocks have undergone regional metamorphism and the effects, particularly with respect to feldspar alteration, are not reported. Plagioclase megacrysts (Lumbers 1972b) and concentrations of garnet crystals as large as 8 cm occur locally in the anorthosite. Iron-titanium oxide concentrations occur as richly disseminated gneissic bands within the anorthosite, and concentrated along the margins of the body.

Economic Activity

Iron-titanium oxide mineralization in anorthosites of Calvin and Papineau townships has been explored and drilled (Lumbers 1972b). Vanadium-bearing titaniferous magnetite occurs at the south end of the Eau Claire body as disseminations and massive lenticular bands ranging in size (hundreds of metres long, 3 to 5 m wide) (Ontario Geological Survey 1984). Shallow pits have been blasted into the garnetiferous anorthosite in Calvin Township. Occurrences of iron, feldspar, beryllium, and mica are indicated on Figure 29 after Lumbers (1972b).

Exposure

Reports from Lumbers (1972b; 1973a; 1976) indicate that exposure varies from large areas of clear bedrock to areas which are covered by Quaternary and recent deposits over large areas. Lumbers' map indicates good exposure over most of the bodies, from 15% or more.

Geochemistry

There is no chemistry available for this body.

Southern Central Gneiss Belt

Anorthosites occurring in the south half of the Central Gneiss Belt are typically more massive with much lower proportions of gabbroic rocks relative to other Grenville Province anorthosites. As well, many of the occurrences are recrystallized, containing portions of clean white anorthosite. Many of these anorthosite occurrences are sheared along their margins. The Arnstein and Whitestone anorthosites are bound along their western margins by the Parry Sound Shear Zone, and these two bodies may represent a single, large body which has been tectonically disrupted (Easton, personal communication). Very long, narrow anorthosite units such as the Moon River-Twelve Mile Bay, Little Lake, Head River-Smudge Lake bodies are common in this part of the Central Gneiss Belt. A few small, unnamed (with the exception of the Doeskin Lake Anorthosite) anorthosite slivers occur along domain boundaries. These small anorthosite units are not described. Property scale reports have been compiled on the following occurrences: Arnstein, Raganooter, Whitestone, Parry Island, Moon River-Twelve Mile Bay, Little Lake and Head River-Smudge Lake anorthosites.

Arnstein Anorthosite (31E/13)

The Arnstein Anorthosite (Figure 30) covers the northeast and southwest corners of East Mills and Ferrie townships respectively, near Parry Sound. The crescent shaped body covers an area of approximately 80 km^2. Access to the body is provided by cottage roads south from Highway 522 near Golden Valley and Arnstein, and ATC trails north from Maple Island.

Geology

This Middle Proterozoic anorthosite lies within the Parry Sound Domain of the Central Gneiss Belt. The body is composed mainly of gabbroic anorthosite, lesser anorthositic gabbro and anorthosite with rare gabbro and pyroxenite phases (McRoberts and Tremblay 1989).

The mineralogy is consistent with granulite facies metamorphism (Marmont and Johnston 1987) consisting of plagioclase with minor scapolite, clinopyroxene, garnet and hornblende (Marmont 1988). The plagioclase is granular, fine grained (2 mm diameter), and occasionally contains minor scapolite and sericite inclusions (Marmont 1988). Amoeboid clots of mafic minerals are abundant within the central portions of the body and aggregates consisting of hornblende ± clinopyroxene form gneissic layers at the margins of the anorthosite (McRoberts and Tremblay 1989). Most pyroxenes have been completely altered to hornblende (Marmont et al. 1988).

Subophitic textures are widespread and igneous layering occurs locally (McRoberts and Tremblay 1989). Centimetre scale mineralogical layering is reported by Marmont et al. (1988) with areas of 90% anorthosite occurring only as a band in the east-central part of the body and a small area southeast of Long Lake. These areas may be considered preferred targets for exploration.

Gneissosity and foliations parallel the contacts of the unit, dipping 18° to 50° to the east-southeast (Marmont 1988). Moderate to weakly foliated rocks occur through-

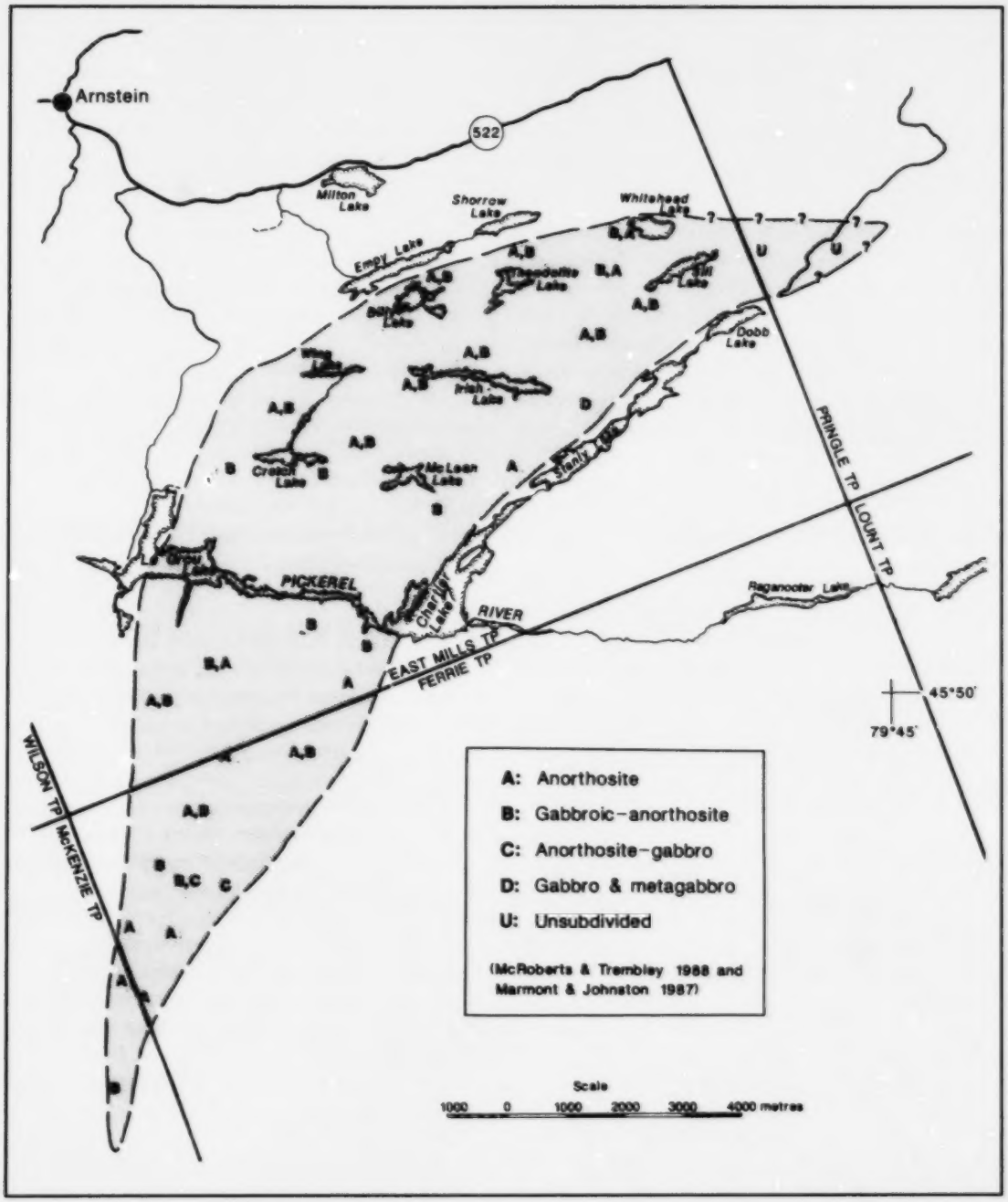


Figure 30. Arnstein Anorthosite.

out the central portions of the body (McRoberts and Tremblay 1989). Foliation in the rocks exhibits variable degrees of intensity, the most strongly foliated rocks occurring at the margins. Pegmatitic facies occur in the eastern portion of the anorthosite (Marmont 1988).

Economic Aspects

There are no documented mineral occurrences in the Arnstein Anorthosite (Assessment Files Research Office; Mineral Deposits Inventory Folio).

Exposure

The south half of the Arnstein Anorthosite has recently been mapped by McRoberts and Tremblay (1989) who report that parts of the body are topographically prominent, and that 15 to 20% of the body is exposed (McRoberts, personal communication 1989) with outcrop easily discernable from aerial photographs. The preliminary geological map by Marmont and Johnston (1987) covers the northern half of the body. All but the northeasternmost tip of the body appears to be well exposed.

Geochemistry

Major and trace element analyses are provided for 26 anorthosite samples (Table 36). It is important to note that designated samples were collected from areas particularly high in feldspar and may not be representative of the overall chemistry (Marmont personal communication 1989).

Geochemical analyses show that Al_2O_3 values are uniformly high, averaging 29%. Alkali content averages 16.3% for 26 samples.

RAGANOOTER ANORTHOSITE (31E/13)

The Raganooter body is situated due south of Highway 522 between the towns of Golden Valley and Commanda, straddling the Pringle and Lount township boundaries in the District of Parry Sound. Lumbering roads west from Trout Creek provide access to within 1 km of Raganooter Lake (McRoberts, personal communication 1989). South of Golden Valley, cottage access roads lead to Little River Lodge where ATC trails provide access to the body.

Geology

The Raganooter Anorthosite (Figure 31) sits within the Central Gneiss Belt of the Grenville Province. The body is east trending and crescent shaped. The southwest corner of the crescent was recently mapped by McRoberts and Tremblay (1987). The dominant lithology is gabbroic anorthosite (McRoberts and Tremblay 1989; Marmont et al. 1988). Textures within the gabbroic anorthosite are however, widely variable. Grain size ranges from fine, usually white recrystallized plagioclase to coarser, inclusion filled, (Marmont 1988) grey or purple plagioclase. Granoblastic, subophitic and blastoporphyritic textures are described (McRoberts and Tremblay 1989; Marmont et al. 1988). Hornblende and pyroxene are the major mafic minerals present and often occur with fine grained garnet rims (Marmont 1988). Fine grained scapolite locally replaces the plagioclase (McRoberts and Tremblay 1989).

A few small, 1 to 10 cm wide mafic dikes crosscut the Raganooter body (McRoberts and Tremblay 1989).

Economic Aspects

Examination of the mineral deposit inventory records (Toronto, Assessment Files Research Office) indicated that there are no known mineral occurrences. McRoberts and Tremblay (1989) report the same.

Exposure

McRoberts and Tremblay (1989) report that the southern portion of the complex, covered on Map P. 3123, is exposed over approximately 10% of its area. The rest of the Raganooter body has not been mapped and the extent of exposure is unknown.

Geochemistry

Ten analyses (previously unpublished) of the more prospective parts of the body, have been provided courtesy C. Marmont and are listed in Table 37. These samples have been purposely selected to characterize areas of high feldspar content and are not necessarily representative of the bulk composition. The percent Al_2O_3 is consistently above 25%. The total alkali content is remarkably consistent, exceeding 16% in all ten samples.

WHITESTONE ANORTHOSITE (41H/09, 31E/12)

The Whitestone Anorthosite is a large body situated in McKenzie, Hagerman, East Purpee and McKellar townships, 5 km northeast of Parry Sound. The body is bounded by Highway 124 to the east and the Canadian National Railway in the west, covering an area 260 km^2 (Kretschmar and McNutt 1971). Access to the interior is provided by smaller roads branching from Highway 124 and south from Highway 520, between Ardbeg and Maple Island.

Geology

The Whitestone Anorthosite (Figure 32) lies within the Parry Sound Shear Zone at the base of the Parry Sound Domain (Marmont 1988) in the Grenville Province. Zircon dating near Mill Lake has given an age of 1350 ± 50 Ma (van Breemen et al. 1986). The body is north-trending and teardrop shaped, exceeding 12 km in length. The width averages 4 km in the north and progressively narrows towards the south.

Rock types range from anorthositic gabbro through to anorthosite (Marmont 1987). The bulk composition is gabbroic anorthosite (Marmont 1988). The body has been subdivided in several ways, with map units based on several criteria, namely iron content (Mason 1969), texture (Mason 1969; Marmont 1988) and mineralogy

Table 36
Chemistry of the Arnstein Anorthosite

%	86MMJ2002	86MMJ2005	86MMJ2023	86MMJ2025	86MMJ2033
SiO_2	48.70	50.20	53.20	51.10	54.50
Al_2O_3	30.20	28.50	29.00	28.70	24.00
Fe_2O_3	1.47	1.84	0.67	1.36	2.23
MgO	0.63	0.45	0.14	1.20	1.02
CaO	13.70	12.70	10.50	12.40	5.71
Na_2O	3.41	3.91	4.96	3.47	5.92
K_2O	0.39	0.80	0.55	0.18	2.46
Ti_2O	0.14	0.16	0.20	0.17	0.13
P_2O_5	0.01	0.01	0.01	0.01	0.01
MnO	0.00	0.01	0.01	0.00	0.01
CO_2	0.32	0.36	0.12	0.27	0.48
S	0.02	0.01	0.01	0.01	0.36
LOI	1.00	1.30	0.30	0.40	2.50
TOTAL	99.99	100.25	99.67	99.27	99.33
$CaO+Na_2O+K_2O$	17.5	17.41	16.01	16.05	14.09
ppm					
V	10.00	15.00	1.00	18.00	14.00
Cr	10.00	10.00	10.00	39.00	22.00
S.G.	2.78	2.80	2.70	2.78	2.78

(Marmont and Johnston 1987)
Sample descriptions are unavailable. It is assumed all samples are anorthosites.

Table 36 continued
Chemistry of the Arnstein Anorthosite

%	88CCM14	88CCM18	88CCM37	88PMZ03	88PMZ07	88PMZ10	88PMZ13
SiO_2	51.96	51.45	51.02	52.02	52.37	51.98	52.92
Al_2O_3	27.98	28.85	28.51	29.30	29.10	28.39	28.53
Fe_2O_3	1.93	1.02	1.59	0.61	0.81	0.95	0.59
MgO	1.27	0.28	1.44	0.31	0.27	0.54	0.33
CaO	10.57	12.45	12.96	11.93	11.19	11.25	10.27
Na_2O	4.22	4.48	3.85	4.51	4.66	4.59	4.80
K_2O	0.85	0.35	0.51	0.50	0.79	0.68	0.91
TiO_2	0.09	0.14	0.12	0.07	0.11	0.12	0.08
P_2O_5	0.07	0.09	0.07	0.06	0.07	0.07	0.04
MnO	0.02	0.01	0.02	0.01	0.01	0.01	0.01
BaO	0.02	0.01	0.01	0.01	0.01	0.02	0.03
LOI	1.27	0.89	0.53	0.47	0.70	0.82	0.82
TOTAL	100.25	100.50	100.65	99.81	100.10	99.43	99.34
$CaO+Na_2O+K_2O$	15.64	17.28	17.32	16.94	16.64	16.52	15.98

The above analyses consist of unpublished data provided courtesy C. Marmont. Sample descriptions are unavailable at this time. All of the above samples are anorthosites and have been collected from most feldspar-rich parts of the body, with the exception of sample 88PMZ2 (anorthositic gabbro).

86MMJ2035	86MMJ2037	86MMJ2042	86MMJ2050	86MMJ2057	86MMJ2065
47.10	51.10	51.70	51.80	51.80	48.50
25.80	27.00	29.70	26.00	29.00	26.00
4.41	2.08	0.67	2.47	0.69	3.42
5.07	1.40	0.04	2.39	0.06	3.68
11.10	12.60	11.40	11.90	11.20	13.40
3.21	3.66	4.33	4.02	4.16	2.15
0.70	0.35	0.57	0.40	1.02	0.51
0.10	0.27	0.12	0.30	0.18	0.45
0.01	0.02	0.01	0.04	0.01	0.01
0.03	0.00	0.01	0.01	0.01	0.04
0.58	0.47	0.32	0.36	0.12	0.37
0.02	0.01	0.01	0.01	0.01	0.02
1.80	0.60	0.90	0.60	1.30	1.00
99.93	99.56	99.78	100.30	99.56	99.55
15.01	16.61	16.30	16.32	16.38	16.06
7.00	49.00	1.00	46.00	2.00	63.00
10.00	37.00	10.00	39.00	10.00	97.00
2.81	2.75	2.66	2.79	2.69	2.79

88PMZ14	88PMZ17	88PMZ23	88CCM11	88CCM27	88CCM30	88PMZ11	88PMZ26
52.74	53.07	52.77	53.41	51.30	52.50	51.88	50.30
29.07	28.28	28.94	28.50	28.08	29.00	29.16	19.28
0.50	0.55	0.51	0.65	1.28	0.49	0.68	8.24
0.22	0.31	0.24	0.28	0.99	0.14	0.19	5.77
10.95	10.04	10.99	11.03	11.82	11.54	11.51	8.88
4.92	5.19	4.74	5.21	4.22	4.84	4.87	3.54
0.75	0.78	0.87	0.16	0.54	0.45	0.69	1.15
0.08	0.07	0.06	0.06	0.10	0.04	0.08	0.80
0.07	0.06	0.08	0.05	0.03	0.07	0.09	0.16
0.01	0.01	0.01	0.01	0.02	0.01	0.01	0.12
0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.04
0.78	0.90	0.73	0.41	0.45	0.33	1.40	0.75
100.01	99.28	99.96	99.79	98.85	99.43	100.60	99.04
16.62	16.01	16.60	16.40	16.58	16.83	17.07	13.57

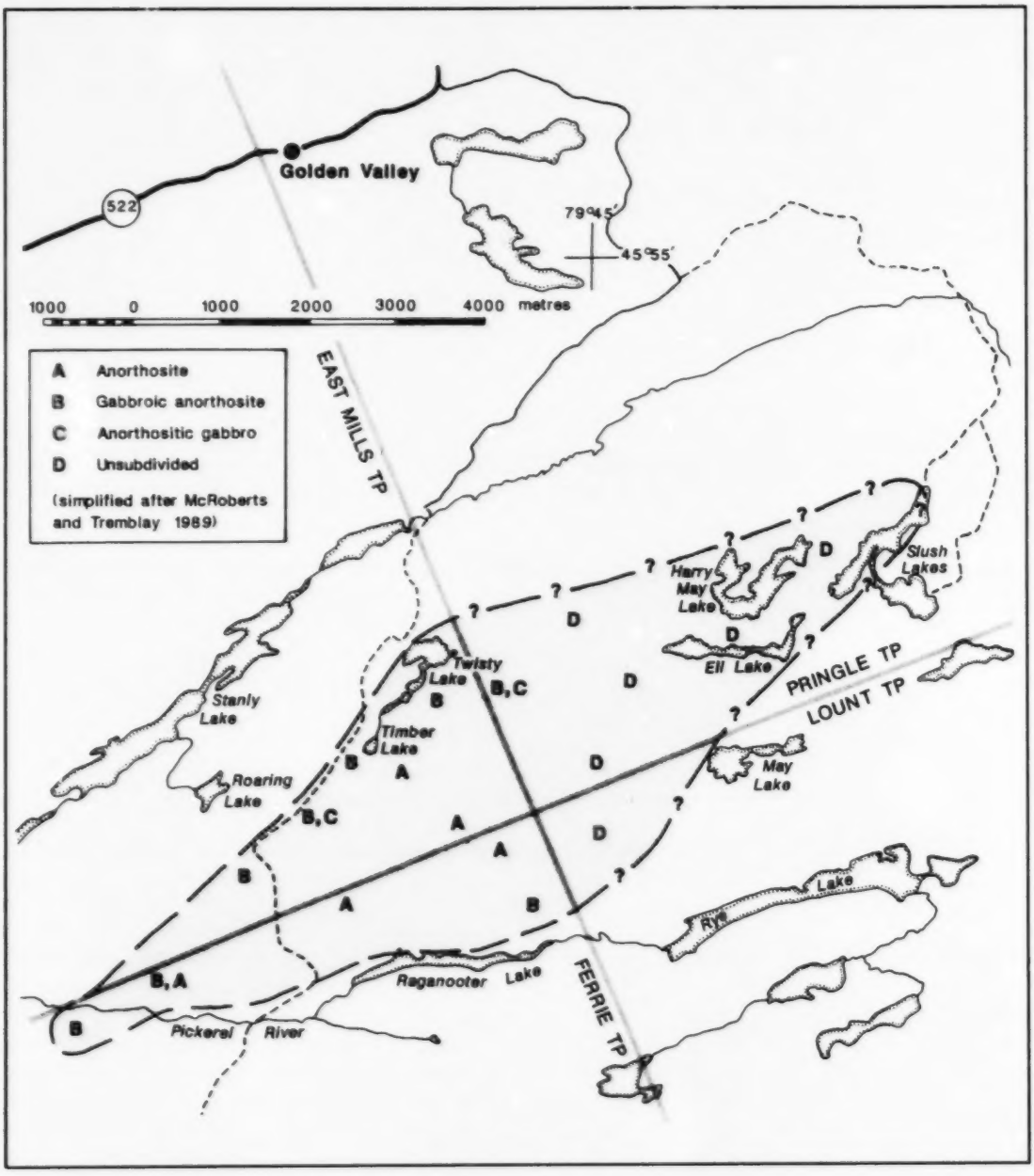


Figure 31. Raganooter Anorthosite.

(Bright 1989). Rocks of anorthosite compositions are typically oikocrystic and porphyritic in texture and units are commonly described in these terms. The porphyritic phases are randomly distributed throughout the oikocrystic facies. Both are composed of plagioclase and clinopyroxene; the oikocrystic phases consist of large, spherical clinopyroxene (1 cm to 30 cm) which subophitically enclose subhedral plagioclase, and the porphyritic phases consist of clinopyroxene and plagioclase phenocrysts without the oikocrystic pyroxene habit (Marmont and Johnston 1987).

The Whitestone Anorthosite is metamorphosed to upper amphibolite to granulite grade. Plagioclase is labradorite (An_{56-66}) in composition (Marmont and Johnston 1987; Marmont 1988), and is variably altered to scapolite. The rims of plagioclase grains are com-

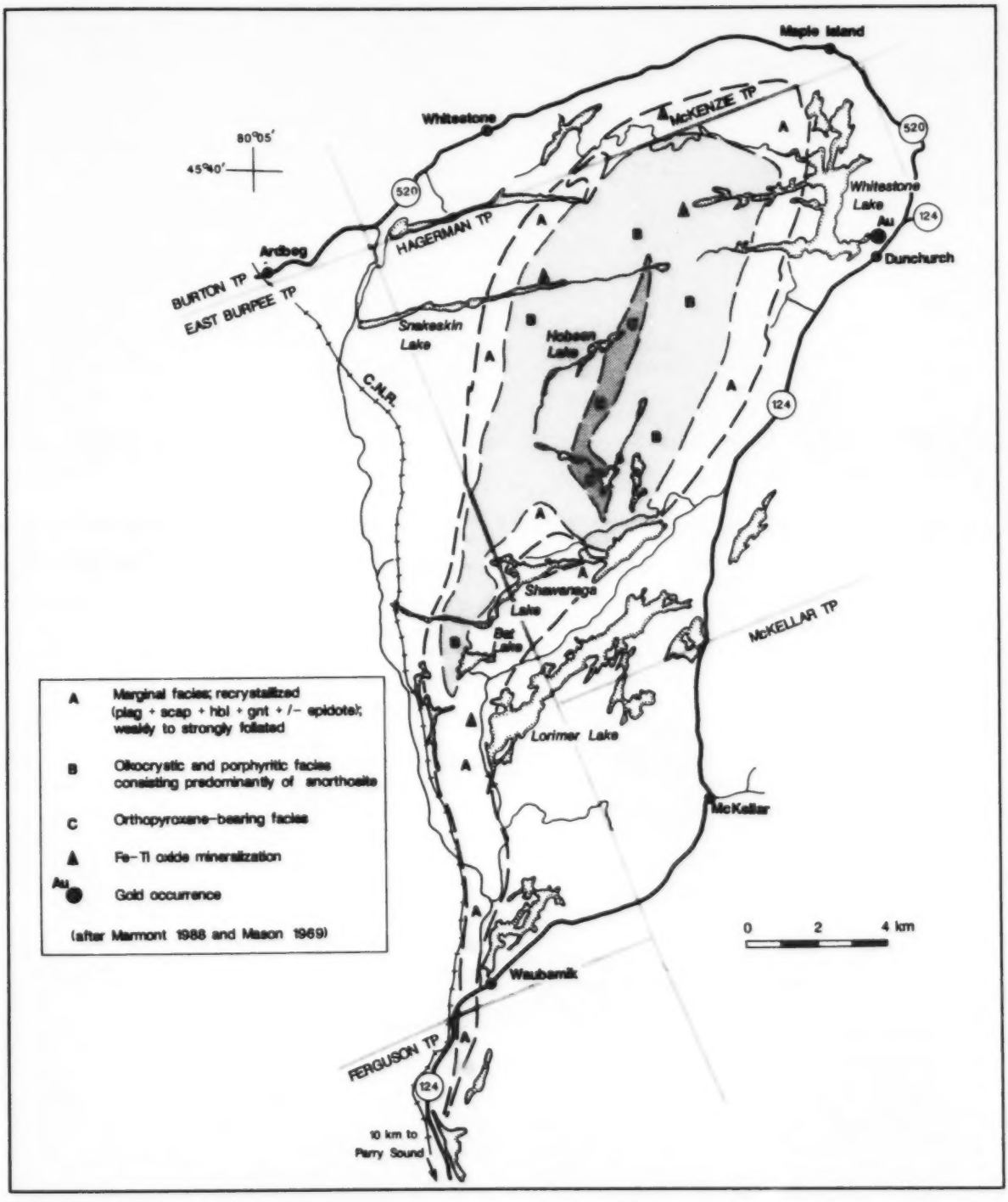


Figure 32. Whitestone Anorthosite.

monly recrystallized, however, inclusions are common in the cores and consist of epidote, amphibole, pyroxene and magnetite. Minerals common in the matrix include clinopyroxene, orthopyroxene, hornblende, scapolite, magnetite, ilmenite, garnet, epidote, titanite, biotite, muscovite and calcite.

Table 37
Chemistry of the Raganooter Anorthosite

	88CCM40	88CCM43	86CCM41	88CCM46
SiO2	52.11	51.34	51.51	53.15
Al2O3	28.41	26.94	27.93	28.13
Fe2O3	1.34	2.80	1.32	1.03
MgO	0.54	1.21	0.55	0.51
CaO	11.82	11.75	11.88	11.05
Na2O	4.50	4.46	4.49	4.84
K2O	0.52	0.51	0.41	0.54
TiO2	0.17	0.46	0.21	0.12
P2O5	0.07	0.08	0.06	0.06
MnO	0.01	0.03	0.02	0.01
BaO	0.02	0.02	0.03	0.02
LOI	0.27	0.19	1.53	0.53
TOTAL	99.79	99.80	99.95	100.00
CaO+Na2O+K2O	16.84	16.72	16.78	16.43

All samples are anothosite, or gabbroic anorthosite. Samples CCM43-CCM46 are from the most prospective part of the Raganooter Anorthosite. These analyses are unpublished data, courtesy C.Marmont, Geologist, M.N.D.M., Dorset.

Marmont et al. (1988) comment that oxide inclusions occur in relict igneous plagioclase crystals, but are present to only a minor extent in most of the plagioclase which is completely recrystallised. Cleaner, more recrystallised plagioclase occurs around Blue Lake (Marmont et al. 1988) and at the centre of the body (Mason 1969), but silicate and oxide inclusions are still abundant (Marmont et al. 1988). A large area in the northeast section, covering 5 km^2 or more, consists of relatively uniform anorthosite (Bright, personal communication) and may represent higher feldspar potential.

The body is strongly deformed along its margins and southern tail. Igneous layering, from decimetre to metre scale, is present in the central part of the body (Marmont 1987) and gneissic layering prevails at the margins where mafic content is higher. Cross-cutting features include east-trending lineaments, some of which are occupied by mafic dikes (Marmont 1987).

The abundance of mafic material in the layered anorthosite, lineament and jointing patterns, and most importantly the distribution of oxide inclusions in feldspars, will be the major factors in determining feldspar potential for the Whitestone body.

Economic Aspects

There are several iron-titanium oxide occurrences in the Whitestone Anorthosite. The oxide minerals hemo-ilmenite, magnetite and minor ferrian ilmenite are concentrated within the mafic clots at the margins. Oxide minerals are also present as finely disseminated inclusions (Kretschmar and McNutt 1971) in feldspars, pyroxenes and amphiboles of the anorthosite. Occurrences are indicated on the map, after Marmont and Johnston (1987).

Exposure

The body as a whole is well exposed, with approximately 35% outcrop. The east arm of Whitestone Lake is an easily accessible area with good exposure (Mason 1969).

Geochemistry

Analyses of anorthosites (Table 38) are listed from Mason (1969) (see also Marmont 1988). The Whitestone body has been sampled extensively by both Marmont and Mason and analyses given are considered representative. Of the fifteen analyses listed, Al_2O_3 content varies from 20.53 to 29.10 weight %, averaging 25.75 weight %. The total alkali content for each analysis is not listed, however the range of values is 13.89 to 18.76 weight %, with an average of 14.89 weight % for all fifteen analyses.

Rare earth element patterns in the Whitestone Anorthosite may also affect mineral potential. Barker (1972) details aspects of R.E.E. patterns in the Whitestone Anorthosite.

More detailed information on the iron-titanium oxide inclusions is given by Kretschmar and McNutt (1971).

88CCM44	88CCM55	88CCM73	88CCM94	88CCM84	88CCM95
52.33	52.32	52.16	52.66	52.00	50.79
27.99	28.46	28.98	28.98	26.66	26.84
1.20	1.27	0.59	0.59	3.11	3.88
1.03	0.41	0.17	0.17	1.21	1.65
10.34	11.94	11.29	11.29	11.81	11.65
4.46	4.55	4.73	4.73	4.47	4.04
1.33	0.58	0.70	0.70	0.58	0.49
0.10	0.14	0.08	0.08	0.49	0.66
0.05	0.09	0.06	0.06	0.07	0.05
0.02	0.02	0.01	0.01	0.05	0.04
0.05	0.03	0.02	0.02	0.01	0.01
1.25	0.53	0.43	0.43	0.22	0.31
100.15	100.20	99.73	99.73	100.70	100.40
16.13	17.07	16.72	16.72	16.86	16.18

Parry Island Anorthosite (41H/08)

The Parry Island Anorthosite (Figure 33) occurs on the west half of Parry Island and the islands off the west shore of Parry Island in Georgian Bay. The body can be accessed by road, 8 km southeast from Parry Sound through the Parry Island Indian Reserve (permission must be granted beforehand). Alternate access is more readily available by boat from either Five Mile Bay in the south or Wabuno Channel via Depot Harbour. The Canadian National Railway reaches Depot Harbour on the northeast side of the island. The body covers an area of approximately 30 km^2.

Geology

Little is known about the Parry Island Anorthosite. The body is teardrop shaped, and lies within the sheared western boundary of the Parry Sound tectonic domain (Easton 1991).

The area has never been mapped in detail and the extent of anorthositic units is unknown. Reconnaissance surveys of several small islands west of Parry Island (Marmont 1988) reveal a mixed assemblage of anorthosite, gabbroic anorthosite, garnetiferous gabbro and anorthositic gabbro. The anorthosite extends to islands in Wabuno Channel (Hewitt 1967). It is medium grained and composed almost entirely of equant labradorite, with minor to trace biotite, hornblende, pyrite and carbonate (Hewitt 1967). Megacrystic textures are common, with plagioclase crystals up to 25 cm long (Marmont 1988). These large relict grains are dark and cloudy, probably indicating the presence of abundant inclusions. A matrix of lighter recrystallized plagioclase surrounds the larger grains. Removal of the inclusions during mineral processing may present problems.

Mafic minerals are also megacrystic in places with orthopyroxene relicts up to 50 cm in length. Mafic clots of clinopyroxene and hornblende (Marmont et al. 1988) within the anorthosite are commonly flattened into discontinuous lenses.

Gneissic textures predominate at the margins of the body as do amphibolite bands (Hewitt 1967).

Economic Aspects

The only known mineral occurrence is the presence of garnet at the northeast margin of the body (Hewitt 1967). Areas of very coarse plagioclase in the Parry Island Anorthosite may have high potential.

Exposure

Marmont's reconnaissance work describes well washed exposures along the shores of the small islands to the west of Parry Island. Since the interior parts of the body have not been mapped in detail, the percentage exposure cannot be determined, however, Hewitt (1967) reports low lying, swampy topography in the centre of the body on Parry Island.

Table 38
Geochemistry of the Whitestone Anorthosite

	MAS002	MAS013	MAS017	MAS020	MAS030	MAS079	MAS134
SIO_2	51.73	53.81	54.00	51.68	52.19	51.42	52.51
AL_2O_3	20.53	22.46	21.99	22.71	27.35	22.19	27.11
FE_2O_3	2.86	1.28	1.10	1.50	0.61	1.06	0.66
FEO	6.64	4.70	3.81	5.14	1.46	2.80	1.81
MGO	1.99	1.99	2.07	1.56	1.00	2.45	1.37
CAO	9.76	9.69	11.03	10.37	11.55	12.32	10.57
NA_2O	3.21	4.03	3.60	3.88	3.80	3.90	3.92
K_2O	0.92	0.56	0.81	0.52	0.44	0.69	0.45
TIO_2	1.51	0.92	0.72	1.12	0.25	0.37	0.26
H_2O	n.d.	0.51	n.d.	0.48	n.d.	n.d.	n.d.

MAS002: foliated, plagioclase 57%, amphibole 17%, scapolite 10%, pyroxene. 7%, + garnet, epidote, omphocite, sphene.
MAS013: foliated, plagioclase 72%, amphibole 14%, garnet. 7%, sphene 5%, pyroxene 4%, +omphocite.
MAS017: foliated, plagioclase 79%, scapolite 9%, pyroxene 4%, amphibole 4%, garnet. 4%, + omphocite, sphene.
MAS020: foliated, plagioclase 43%, scapolite 29%, amphocite 19%, garnet 8%, + omphocite
MAS030: foliated, plagioclase 59%, scapolite 18%, amphibole 21%, + garnet, epidote, omphocite.
MAS079: foliated, plagioclase 50%, scapolite 29%, amphibole 14%, pyroxene 6%, + sphene.
MAS134: glomeroporphyritic, plagioclase 97%, + pyroxene, amphibole, omphocite.
MAS144: glomeroporphyritic, plagioclase 82%, pyroxene 5%, amphibole 3%, + scapolite, garnet, omphocite.

Geochemistry

Eight analyses, provided courtesy C. Marmont, are listed in Table 39. These samples (except 88CCM213) were collected during the 1988 field season and represent areas with the highest feldspar content. The average alumina content for anorthositic samples (anorthosites and anorthositic gabbros) is relatively high at 27.44 weight %. The average alkali content for the anorthosites is 16.14 weight %.

Moon River and Twelve Mile Bay Anorthosites (41H/01, 31E/04)

The Moon River Anorthosite is a long narrow sheet, the southern end of which is the Twelve Mile Bay Anorthosite. The north end of the Moon River body extends south from the junction of Highways 69 and 612, approximately 30 km south of Parry Sound. Highway 612 roughly follows the shape of the body, curving to the southwest. Access is provided by minor roads, leading west from Highway 69, to Arnold's Bay Marina. The body has an areal extent of at least 10 km^2, outcropping over a length of 40 km (Marmont 1987).

Geology

The Moon River and Twelve Mile Bay anorthosites occur in the Parry Sound Domain of the Central Gneiss Belt. The Moon River Anorthosite is a long (100 to 200 m wide) and narrow, folded sheet within the Moon River synform (Figure 34). The south limb of the anorthosite swells to over 1 km in width at Twelve Mile Bay. Three narrow finger-like bodies extend to the west the length of Twelve Mile Bay. The body varies in thickness from a few kilometres in the Twelve Mile Bay area to a few tens of metres to the north and south. The Twelve Mile Bay Anorthosite may be a branch of the Moon River body or it may be a separate body at a lower structural level (Marmont 1987).

The mineral assemblage consists predominantly of white plagioclase, with minor to accessory: hornblende, biotite, muscovite-sericite, chlorite, epidote, scapolite, titanite, quartz, orthoclase, magnetite, garnet, and calcite (Marmont 1987). There is minor alteration of plagioclase to sericite (Marmont 1987).

Texturally the anorthosite consists of a mosaic of fine grained (2 mm) labradorite plagioclase with some oikocrystic grains and abundant, irregular fractures (Marmont 1987). Layering is pervasive, particularly in the northern part of the body, where tectonic layering is characterized by white, granoblastic 1 to 25 cm thick anorthosite bands interlayered with darker 1 to 10 cm thick, mafic bands (Marmont 1987).The segregation of mafic minerals into bands may prove beneficial for mineral separation however the abundance of mafic bands may negatively affect the overall alumina and alkali content.

MAS144	MAS181	MAS218	MAS260	MAS283	MAS297	MAS106	MAS336
52.16	53.92	52.57	51.85	52.11	51.99	48.08	53.15
27.86	29.10	27.82	26.90	25.03	25.03	26.60	22.74
0.64	0.27	0.49	0.71	1.00	1.00	0.89	1.97
0.92	0.27	0.88	2.03	2.00	2.00	1.90	3.18
1.06	0.27	0.78	2.08	2.05	2.05	2.39	2.48
12.03	12.34	12.84	11.80	12.84	12.82	16.19	10.76
4.06	4.24	4.05	3.74	3.89	3.89	2.15	3.36
0.61	0.37	0.39	0.24	0.49	0.49	0.42	0.55
0.14	0.08	0.16	0.22	0.36	0.36	0.31	0.62
n.d.	n.d.	n.d.	n.d.	n.d.	n.d. P_2O_5	0.02	0.07

MAS181: glomeroporphyritic, plagioclase 95%, pyroxene 5%, + omphocite.
MAS218: green feldspar facies, plagioclase 75%, pyroxene 20%, amphibole 3%, scapolite 2%, + omphocite, sphene.
MAS260: glomeroporphyritic, plagioclase 92%, pyroxene 2%, + scapolite, amphibole, omphocite.
MAS283: glomeroporphyritic, modes unavailable.
MAS297: glomeroporphyritic, plagioclase 85%, pyroxene 9%, amp. 5%, + scap, omphocite.
MAS160: glomeroporphyritic, modes unavailable.
MAS336: foliated, plagioclase 68%, amphibole 20%, scapolite 4%, pyroxene 4%, garnet. 2%, + omphocite sphene.
(Mason 1969)

Table 39
Chemistry of the Parry Island Anorthosite

wt.%	88CCM201	88CCM202	88CCM204	88CCM207	88CCM213	88CCM206	88CCM208	88CCM210
SiO_2	52.82	55.74	52.56	58.14	55.64	52.85	52.75	48.9
Al_2O_3	28.88	27.56	29.37	24.9	25.79	27.29	28.29	14.96
Fe_2O_3	0.51	0.85	0.75	1.09	1.53	1.39	0.72	11.03
MgO	0.28	0.36	0.38	0.42	0.82	0.47	0.41	7.28
CaO	11.4	9.59	12.06	6.62	8.96	10.02	10.8	9.27
Na_2O	4.66	5.62	4.59	6.76	5.41	5.01	4.75	2.72
K_2O	0.36	0.49	0.32	1.26	0.41	0.6	0.42	1.36
TiO_2	0.05	0.1	0.07	0.18	0.29	0.26	0.09	1.05
P_2O_5	0.02	0.05	0.06	0.13	0.07	0.05	0.04	0.79
MnO	0.01	0.01	0.01	0.01	0.01	0.01	0.01	0.12
BaO	0.01	0.02	0.01	0.09	0.03	0.02	0.02	0.03
LOI	0.87	0.46	0.31	0.66	0.88	0.41	0.44	1.27
TOTAL	99.88	100.85	100.5	100.25	99.85	98.39	98.75	98.79

The above analyses are unpublished data, provided courtesy C. Marmont. Many of the samples were selected from high feldspar areas of the Parry Island body, and may not be representative of the bulk chemistry. All samples except 88CM207, 88CCM210 and 88CCM213 are anorthosites.
88CCM207: anorthositic gabbro (Marmont personal communication).
88CCM213: anorthositic gabbro (Marmont personal communication).

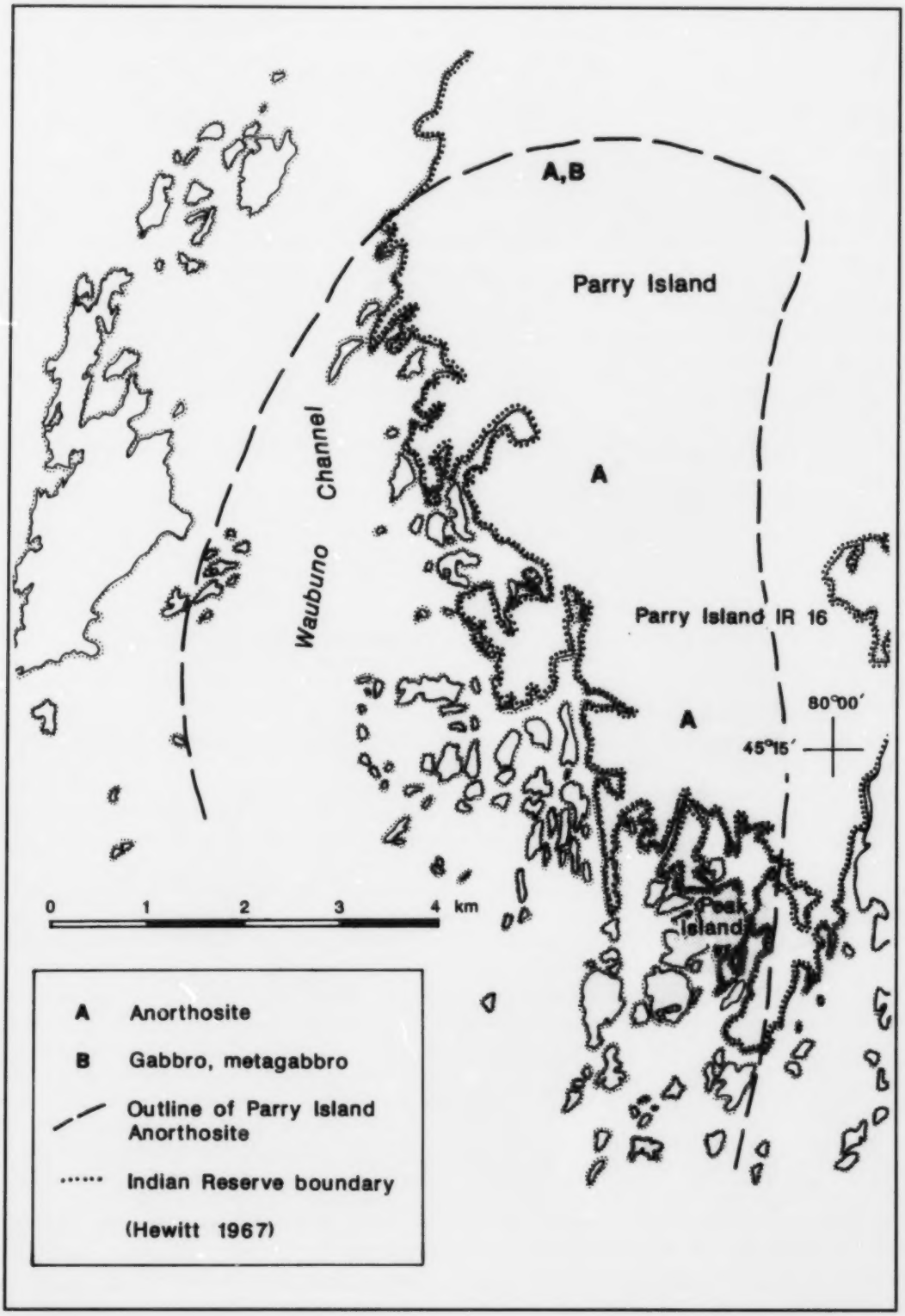


Figure 33. Parry Island Anorthosite.

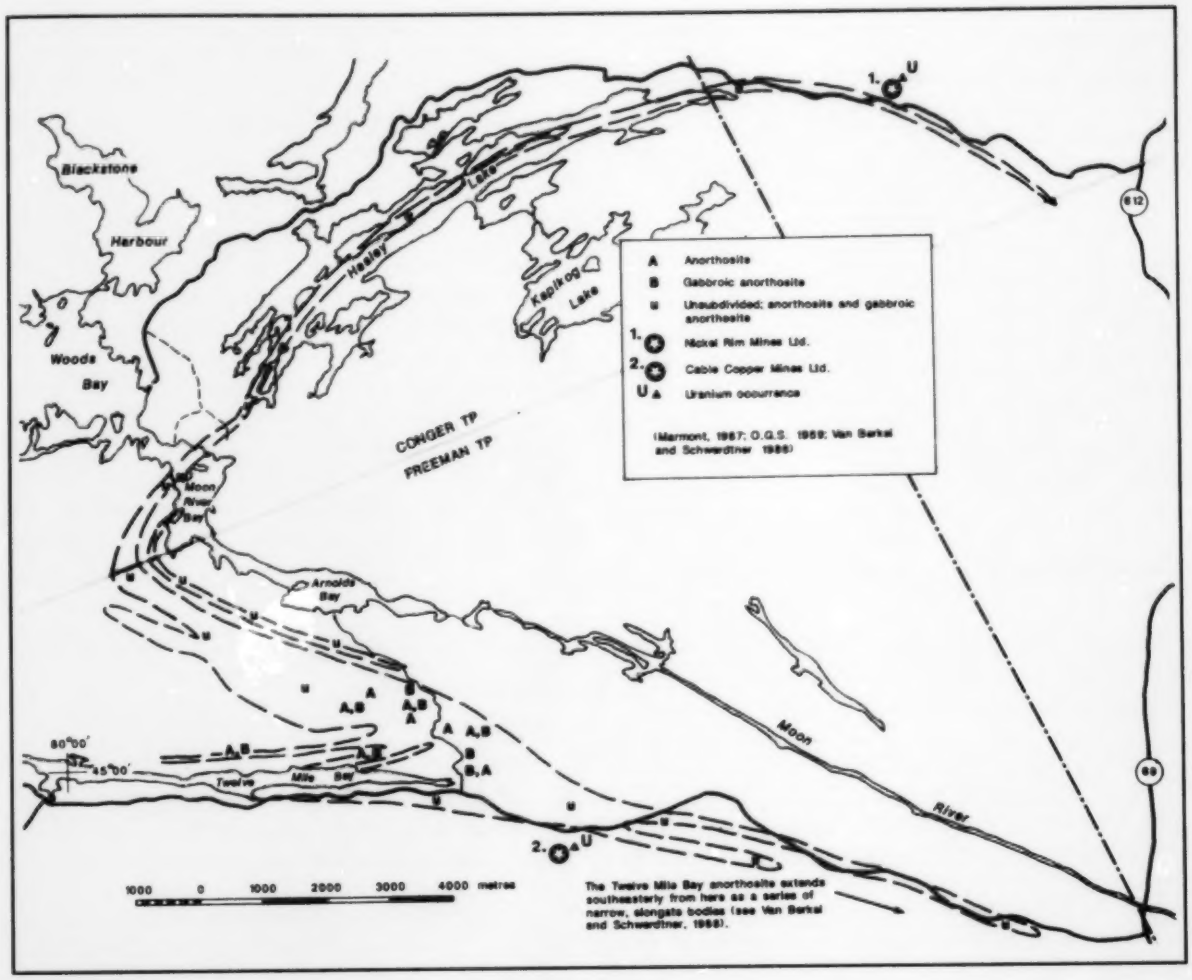


Figure 34. Moon River and Twelve Mile Bay Anorthosite.

Economic Aspects

The Nickel Rim Mines Ltd., Cable Copper Mines Ltd. and a small uranium occurrence all lie within a few hundred metres of the anorthosite sheet, occurring in the surrounding gneissic country rocks (Van Berkel and Schwerdtner 1986). There are no known connections between the mineralization and the Moon River and Twelve Mile Bay anorthosite. The anorthosite itself does not host this mineralization.

Exposure

Hilly relief provides moderate to good exposure and the bush road to Arnold's Bay Marina provides good cross sectional access (Marmont 1987). Swampy topography unfortunately covers the wider expanses of the body (Marmont 1987).

Geochemistry

Fifteen anorthosite analyses are given by Marmont (1987). The Al_2O_3 values are consistently high, averaging 27.1%. The total alkali contents are relatively high as well, ranging from 15.56% to 17.02% (averaging 16.38%). Three additional analyses were made available by C. Marmont (Dorset Resident Geologist's Office, Ministry of Northern Development and Mines). These analyses are listed in Table 40 together with three analyses from Marmont (1987).

Little Lake Anorthosite (31D/13)

The Little Lake Anorthosite consists of two, long narrow sheets located just north of Port Severn in Baxter Township. The units extend south from Macy's Bay for 12 km. The units are transected by Highways 69 and 5 (Figure 35). Shoreline exposures are easily accessible on both Barron's Lake and Little Lake.

Table 40
Chemistry of the Moon River Anorthosite

wt.%	88CCM161	88CCM164	88CCM168	87CCM0010	87CCM0016	87CCM0027
SiO_2	52.82	51.88	52.43	52.95	51.13	52.10
Al_2O_3	29.39	29.17	29.64	28.12	27.17	27.92
Fe_2O_3	0.92	0.83	0.56	1.50	2.46	1.82
MgO	0.31	0.24	0.14	0.88	1.97	1.05
CaO	11.85	12.33	11.97	11.57	11.15	11.22
Na_2O	4.74	4.4	4.68	4.17	3.31	4.30
K_2O	0.3	0.35	0.34	0.64	1.10	0.80
TiO_2	0.13	0.08	0.08	0.14	0.23	0.15
P_2O_5	0.07	0.08	0.06	0.07	0.20	0.22
MnO	0.01	0.01	0.01	0.02	0.04	0.03
BaO	0.01	0.01	0.01	-	-	-
LOI	0.24	0.24	0.43	0.54	0.80	0.49
TOTAL	99.63	99.63	100.35	100.65	99.56	100.10
$CaO+Na_2O+K_2O$	16.89	17.08	16.99	16.38	15.56	16.32

All the above unpublished data were provided courtesy C. Marmont; these samples represent areas with particularly high feldspar proportions.
The above samples i.e. 87CCM0010, 87CCM0016 & 87CCM0027 are representative analyses of the Moon River Anorthosite.
(Marmont 1987)

Geology

The Little Lake Anorthosite forms a distinct lithology in the predominantly granitoid gneiss terrane of the Muskoka Domain in the Central Gneiss Belt (Van Kranendonk 1985). The unit consists of two subparallel, east-west trending units which have an estimated maximum thickness of 200 m. Possibly originally dikes or sills, the Little Lake units are thin (50 to 200 m width) but elongate, continuous over a length of 8 km (Van Kranendonk 1985). Contacts with the surrounding quartzofeldspathic gneisses are sharp and parallel the regional foliation (Van Kranendonk 1985). Compositionally, the Little Lake unit resembles massif-type anorthosites (Van Kranendonk 1987) with plagioclase

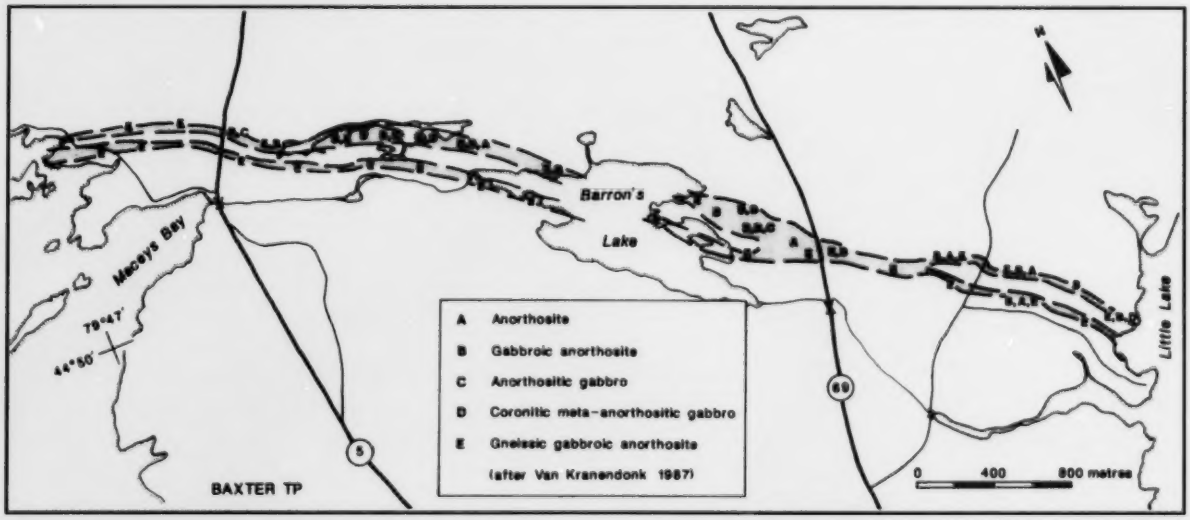


Figure 35. Little Lake Anorthosite.

compositions of An_{40-65}. Igneous layering is preserved locally (Easton 1991), with a general trend from gabbroic anorthosite at the margins gradational to anorthosite at the core (Van Kranendonk 1987). The anorthosite core is typically recrystallized (Van Kranendonk 1985) and gneissic textures are prevalent at the margins (Van Kranendonk 1984). Megacrystic, "leopard rock" (smaller than 1 cm sized grains) is abundant (Van Kranendonk 1985) particularly east of Highway 5. This characteristically coarser textured anorthosite may provide a more favourable target. Gneissic gabbroic anorthosite is predominant west of Highway 5 where folding is evident (Van Kranendonk 1985). Granitic pegmatites are present in the anorthosite and some parts of the anorthosite are oikocrystic (Van Kranendonk 1984). Compositional variations occur gradationally throughout.

Economic Aspects

There are no known mineral occurrences in the Little Lake anorthosites. A megacrystic plagioclase facies directly adjacent to Highway 5 represents a noteworthy feldspar target.

Exposure

The Little Lake Anorthosite is exposed continuously for 8 km of the total 12 km length. North towards Coldwater, the anorthosite becomes less well exposed (Van Kranendonk 1985).

Geochemistry

The PETROCH database supplied sixteen unpublished geochemical analyses of anorthosites in Baxter Township, which are samples from the Little Lake Anorthosite (submitted for analysis by R.M. Easton). Five representative samples are listed in Table 41. The Al_2O_3 content of the sixteen samples averages 27.2%. Alkali content averages 16.09% for the sixteen samples.

Head River and Smudge Lake Anorthosites (31D/15)

The Head River and Smudge Lake anorthosites consist of several similar bodies which each form one or more long narrow units. All but one of these units occur in Digby Township (Figure 36). The Head Lake Oval is exposed on the north shore of Head Lake and on islands offshore, and access is best afforded by boat. The Head River sheet is accessible by Highway 503, 3 km northeast of Uphill. The combined areal extent of the bodies is approximately 2.5 km^2.

Geology

The Head Lake and Smudge Lake sheets lie within the Central Gneiss Belt of the Grenville Province. The bodies are all very narrow (i.e., 100 to 500 m) and elongate. Deformation has disrupted, stretched and folded the bodies.

The four anorthosite bodies consists of: a) The Head Lake Oval, situated for the most part over the northeast end of Head Lake, b) An unnamed, folded anorthosite sheet north of Head River, c) The Smudge Lake Sheet, a boudinaged sheet situated along the southern contact of the Smudge Lake monzonite pluton (0.5 km northwest of Head River sheet), d) A small unnamed body, situated approximately 5 km east of the Head Lake Oval in Somerville Township (Easton 1986).

All descriptions have been derived from Easton (1986) unless otherwise indicated.

The Head Lake Oval consists of brecciated anorthosite, as 20 cm^2 to 2.0 m^2 blocks. Granitic pegmatites crosscut the anorthosite and comprise 5 to 25% of the rock volume. Some 2 to 5 cm scale layering, from anorthositic gabbro to gabbroic anorthosite is present on the mainland exposures, where the body is not brecciated. Mafic minerals consisting of predominantly hornblende, occur as rodded and elongate clots within a plagioclase groundmass. The anorthosite is recrystallized with medium grained, equigranular textures.

The Head River sheet is a 12 to 14 km long sheet, composed of medium to coarse grained, massive, recrystallized anorthosite with minor anorthositic gabbro. Hornblende is present as well-developed aggregates.

The boudinaged anorthosite sheet consists of several en-echelon lenses of brecciated anorthosite, gabbro and gabbroic anorthosite in a monzonite to granite pegmatite matrix. The lower feldspar content and heterogeneity of this rock make it a less favourable target.

The small unnamed body to the east consists of massive anorthosite to gabbroic anorthosite. The body is similar compositionally to the Allsaw Anorthosite and is considered a distinctly different unit from the other Head River units.

The Head River Anorthosite sheet may be the most prospective since it is more homogeneous, with a significant anorthosite component and reasonably good access via Highway 503.

Table 41
Chemistry of the Little Lake Anorthosite

wt.%	A	B	C	D	E
SiO_2	54.20	53.00	50.90	49.80	54.20
TiO_2	0.27	0.16	0.25	0.24	0.11
Al_2O_3	25.70	27.70	28.70	27.50	27.60
Fe_2O_3	0.59	0.03	0.54	0.69	0.18
FeO	1.80	0.68	1.37	1.88	0.77
MnO	0.04	0.01	0.02	0.04	0.02
MgO	1.61	0.12	0.75	1.73	0.55
CaO	10.10	10.60	13.30	12.40	11.00
Na_2O	4.39	5.26	3.56	3.69	4.70
K_2O	0.91	0.38	0.31	0.46	0.50
P_2O_5	0.01	0.10	0.05	0.07	0.07
CO_2	0.23	0.19	0.11	0.30	0.10
S	0.01	0.01	0.02	0.02	0.01
H_2O+	0.44	0.20	0.09	0.37	0.18
H_2O-	0.00	0.00	0.00	0.05	0.00
TOTAL	100.30	98.40	99.90	99.20	100.00
LOI	0.80	0.50	0.40	0.70	0.40
SP.GR	2.74	2.69	2.75	2.77	2.71
$CaO+Na_2O+K_2O$	15.40	16.24	17.17	16.55	16.22
ppm.					
GA	12.0	14.0	18.0	19.0	13.0
NB	-0.5	-0.5	-5.0	-5.0	-5.0
V	16.0	5.0	25.0	30.0	6.0
TH	-10.0	-10.0	-10.0	-10.0	-10.0
RB	7.0	-5.0	-5.0	-5.0	-5.0
SR	640.0	725.0	445.0	450.0	670.0
Y	-5.0	-5.0	-5.0	-5.0	-5.0
ZR	85.0	80.0	60.0	65.0	75.0
Y	5.0	1.0	2.0	2.0	2.0
LA	5.0	2.0	2.0	2.0	3.0
CE	10.0	4.0	4.0	4.0	5.0
PR	1.0	-1.0	-1.0	-1.0	1.0
ND	5.0	2.0	2.0	2.0	2.0
SM	1.0	-1.0	-1.0	-1.0	-1.0
EU	0.6	0.5	0.5	0.5	0.5
GD	1.0	-1.0	-1.0	-1.0	-1.0
TB	1.0	-1.0	1.0	1.0	-1.0
DY	0.9	0.2	0.4	0.5	0.2
HO	2.0	-1.0	1.0	1.0	-1.0
ER	5.0	1.0	2.0	2.0	1.0
TM	1.0	-1.0	-1.0	-1.0	-1.0
YB	0.6	0.1	0.2	0.2	0.2
LU	1.0	-1.0	-1.0	-1.0	-1.0

A : Anorthosite, Baxter Twp. B : Anorthosite, Baxter Twp. C : Anorthosite, Baxter Twp.
D : Anorthosite, Baxter Twp. E : Anorthosite, Baxter Twp.

(unpublished PETROCH data; submitted for analysis by R. M. Easton)

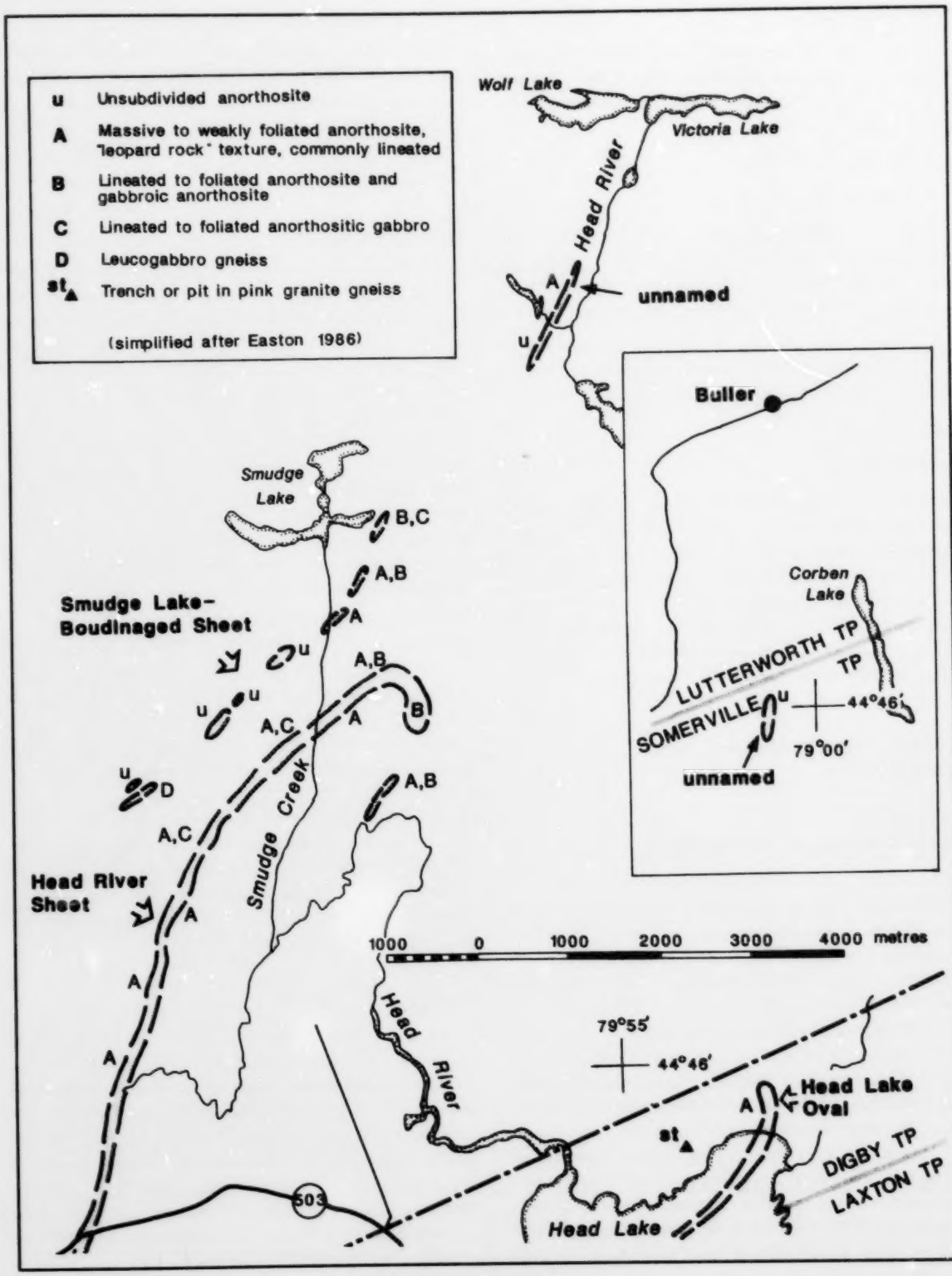


Figure 36. Head River and Smudge Lake Anorthosite.

Economic Aspects

There are no mineral occurrences within the anorthosites as indicated on Easton's map (1986), nor are there any occurrences recorded in the Toronto assessment file records office.

Exposure

The Head Lake Oval is poorly exposed, covered for the most part by Head Lake and low swampy topography (Easton 1986). The best exposure occurs at the north end of Head Lake and on the two northern islands.

The Head River anorthosite sheet is best exposed in the Head River synform, south of Highway 503 to Head River, south of Smudge Lake (Easton 1986).

Geochemistry

Table 42 lists analyses of anorthosites, gabbroic anorthosites and anorthositic gabbros from the Head Lake bodies (Easton 1986). Total alkali content for the six samples is slightly low relative to many other anorthosite bodies, averaging 15.38%. Al_2O_3 values are all above the 20% cutoff, except for one sample from the Head Lake Oval and possibly this analysis is not representative of the body's bulk chemistry.

Central Metasedimentary Belt Anorthosites

Bancroft Terrane Anorthosites

The Percy Lake and Allsaw anorthosites and the Farquhar Lake Complex occur within the Bancroft Terrane of the Central Metasedimentary Belt. The Percy Lake Anorthosite however, may be considered to lie within the Central Metasedimentary Belt Boundary Zone. The Allsaw and Percy Lake bodies appear to be similar mineralogically, comprised predominantly of anorthosite. Anastomosing shears in the Percy Lake body (Marmont et al. 1988) may be comparable with the sheared base of the Allsaw Anorthosite. It is unfortunate that more is not known about the Percy Lake occurrence. The Farquhar Lake Complex consists of four bodies, two with a significant anorthosite component and two which consist of predominantly gabbro and pyroxenite. The anorthosite of the Farquhar Lake complex is an augen gneiss, and bears little resemblance to the other two anorthosite occurrences in the Bancroft Terrane.

Allsaw Anorthosite (31D/15)

The Allsaw Anorthosite is located in Minden Township and consists of a large north-trending body and two much smaller bodies to the southeast. The main body is accessible by Highway 121 approximately 5 km northeast of Minden and has an areal extent of at least 20 km^2.

Geology

This Middle to Late Proterozoic (about 1240 Ma; Easton 1991) anorthosite is surrounded by rocks of the Denna Lake structural zone (Easton 1990) in the Central Gneiss Belt. The body is a relatively flat-lying, tectonic sheet (Easton 1987b), elongate from north to south with an irregular outline. The sheet is characterized by a highly deformed contact with the underlying marble breccias. The underlying marble breccia is exposed in places within the anorthosite body (Easton 1987b). Therefore, where the underlying breccias are exposed, the anorthosite sheet is much thinner. Deformation is progressively weaker toward the top of the sheet where primary igneous textures can be observed (Easton 1987b).

Anorthosite dominates, with only minor zones of gabbroic anorthosite. Recrystallization produces the characteristic, clean (i.e., inclusion-free plagioclase) white anorthosite present throughout most of this body (Marmont et al. 1988). Plagioclase is the major mineral with minor hornblende and biotite also present. Completely recrystallized, granular anorthosite occurs along a 10 m wide shear zone, at the base of the anorthosite sheet. Numerous carbonate veins and granitic pegmatite dikes crosscut the anorthosite (Marmont et al. 1988) and account for up to 20% of the body (Easton 1987b). The heterogeneity caused by this material may negatively affect mineral dressing procedures (Marmont et al. 1988).

Economic Aspects

An overgrown quarry occurs on the north side of Highway 121 on Lot 22 of Concession 5 in Minden Township (Easton 1987). The quarry produced crushed anorthosite in the 1940s for use as road metal. The anorthosite at this location is coarse grained and friable (Easton 1987b). Easy access and good exposure make this area a favourable target for future activity. The area just north of the old quarry, where the power lines converge (Figure 37) represents an area with good potential since it is very well exposed, close to the highway, and the rocks are described by Easton as predominantly massive anorthosites.

Table 42
Chemistry of the Head River Bodies

wt.%	A	B	C	D	E	F
SiO_2	48.20	55.20	49.50	50.10	54.10	51.20
TiO_2	0.48	0.37	1.02	0.28	0.92	0.18
Al_2O_3	25.70	23.00	22.50	27.10	15.60	28.60
Fe_2O_3	2.22	0.15	2.66	1.50	3.25	0.56
FeO	2.91	2.18	3.93	1.75	5.67	0.94
MgO	2.28	1.86	3.04	1.48	5.14	0.76
CaO	12.40	8.98	10.60	11.80	8.73	10.80
Na_2O	3.42	4.87	3.62	3.68	3.42	3.97
K_2O	0.66	0.93	1.27	0.84	1.05	1.24
P_2O_5	0.13	0.12	0.27	0.12	0.12	0.03
MnO	0.08	0.08	0.11	0.05	0.16	0.02
CO_2	0.42	0.27	0.26	0.25	0.07	0.09
S	0.01	0.01	0.12	0.02	0.01	0.01
H_2O+	0.31	0.38	0.65	0.58	0.92	.11
H_2O-	0.05	0.06	0.11	0.11	0.04	0.07
Total	99.20	99.80	99.60	99.70	99.20	99.58
$CaO+Na_2O+K_2O$	16.48	14.78	15.49	16.32	13.20	16.01
ppm						
Ba	210	370	720	250		
Co	15	11	20	12	31	9
Cr	11	18	34	9	154	13
Cu	8	68	96	15	74	8
Li	13	10	14	17		
Mo	3	3	3	3	3	3
Nb	17	9	13	7	8	5
Ni	9	11	22	8	30	22
Pb	16	15	10	11	10	13
Rb	10	10	10	20	8	5
Sc	10	9	13	5		
Sr	1455	1295	1490	1400	320	490
Th	7	5	10	10	10	10
V	155	95	155	90	16	
Y	8	16	23	5	20	5
Zn	46	50	78	38	100	22
Zr	25	25	50	13	115	60

A : anorthositic gabbro, Hwy 503, Head River Sheet
B : anorthosite, Head River Sheet
C : anorthosite, Head River Sheet
D : weathered gabbroic anorthosite, Head River Sheet
E : anorthosite, Head Lake Oval, mainland
F : anorthositic gabbro, Digby area

(Easton 1986)

Exposure

Only 5% of the total areal extent of the anorthosite is exposed, estimated from Map P.3071 (Easton and Van Kranendonk 1987). Exposure is relatively good however, along the northeast-trending powerline which transects the Allsaw body, and along the roadways (Figure 37).

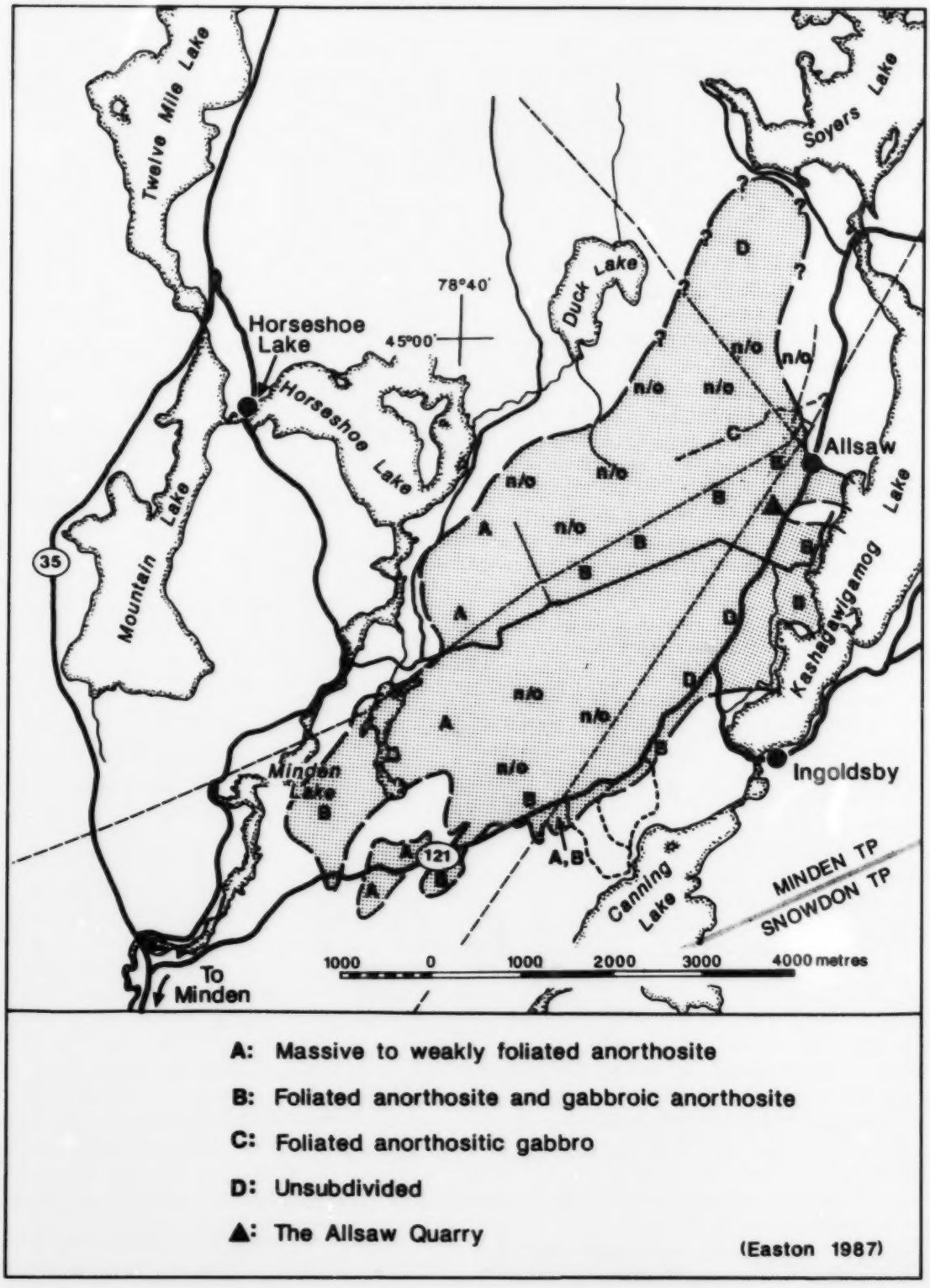


Figure 37. Allsaw Anorthosite.

Geochemistry

Table 43 shows seven analyses. Five analyses are given by Easton (1987b) who lists major and selected trace element geochemistry for the Allsaw Anorthosite. The five samples have Al_2O_3 over 20%, averaging approximately 27%. Easton (1991) remarks

Table 43
Chemistry of the Allsaw Anorthosite

wt.%	84RME-0334	84RME-0335	84RME-0381	84RME-0382	84RME-1151
SiO_2	48.00	49.80	50.90	51.10	50.70
TiO_2	0.03	0.12	0.09	0.10	0.28
Al_2O_3	26.40	27.00	29.30	29.60	26.90
Fe_2O_3	0.00	0.35	0.04	0.01	1.05
FeO	0.65	0.95	0.58	0.44	2.05
MnO	0.03	0.02	0.01	0.01	0.05
MgO	0.39	1.75	0.32	0.19	1.93
CaO	13.80	13.70	12.60	12.60	12.10
Na_2O	5.37	4.23	5.22	4.43	3.61
K_2O	0.82	0.36	0.48	0.38	0.58
P_2O5	0.07	0.00	0.01	0.01	0.00
H_2O+	0.23	0.17	0.29	0.22	0.74
H_2O-	0.07	0.07	0.01	0.02	0.05
CO_2	2.37	0.99	0.63	0.58	0.40
LOI	3.00	0.40	0.80	0.60	0.60
TOTAL	98.70	99.60	99.70	99.80	100.40
$CaO+Na_2O+K_2O$	19.99	18.29	18.30	17.41	16.29

wt.%	88CCM0114	88PMZ0075
SiO_2	51.91	50.26
Al_2O_3	29.71	28.52
Fe_2O_3	0.77	0.79
MgO	0.2	0.48
CaO	12.32	12.88
Na_2O	4.61	4.60
K_2O	0.58	0.59
TiO_2	0.09	0.07
P_2O_5	0.05	0.15
MnO	0.01	0.01
BaO	0.02	0.06
LOI	0.41	1.54
TOTAL	98.39	99.96
$CaO+Na_2O+K_2O$	17.51	18.07

88RME-0334, Allsaw anorthosite, scapolitized, foliated
88RME-0335, Allsaw anorthosite, foliated, with gabbroic phases
88RME-0381, Allsaw anorthosite, foliated
88RME-0382, Allsaw anorthosite, foliated
88RME-1151, Allsaw anorthosite, massive to weakly foliated (Easton 1987)
88CCM0114 & 88PMZ0075 - Unpublished analyses provided courtesy C. Marmont, samples selected to represent anorthosites with high feldspar contents.

upon the distinctly different REE geochemistry for the Allsaw Anorthosite relative to anorthosite bodies of the Central Gneiss Belt, with a pattern which resembles that of rocks from the Gooderham Syenite Belt to the southeast. Rare earth element geochemistry may be a factor to consider in mineral processing.

The two other samples listed were collected by C. Marmont from areas with the highest feldspar content. It is important to note that these samples are not representative of the body as a whole. Al_2O_3 content is also high in these two samples at 29.71% and 28.52%. Total alkali content for the seven samples averages 17.98%.

Percy Lake Anorthosite (31E/01)

The Percy Lake body lies within Bruton and Harburn townships, at the south end of Algonquin Provincial Park. The nearest major access is north from Haliburton (on Highway 121) via County Road 19 to Fort Irwin. Smaller roads approximately 5 km northeast of Irwin access the Percy Lake intrusion. The Percy Lake body covers an area 40 km^2.

Geology

The body is east trending (Figure 38), roughly lens shaped, situated in the Central Metasedimentary Belt Boundary Zone of the Grenville Province. The following description is summarized from Marmont, et al. (1988). It consists predominantly of anorthosite with lesser gabbroic anorthosite. The plagioclase is characteristically very white, but is locally observed as large (up to 6 cm in length) grey phenocrysts. Biotite, hornblende, and muscovite bands are unevenly distributed throughout.

Tectonic disruption of the body has resulted in brecciation and some grain size reduction, including rotated blocks of the anorthosite. Numerous, anastomosing shears, ranging from metres to tens of metres in width, crosscut the body. Approximately 5% of the body is composed of medium to coarse, granitic to monzonitic material, occurring along these shears with variable degrees of mylonitization. The degree of inhomogeneity with regards to textures and lithology may negatively affect industrial mineral potential.

Economic Aspects

There is no record of mining activity in the area of the Percy Lake Anorthosite (Assessment Files Research Office), and there are no records of mineral deposits in the area (Mineral Deposits Inventory Folio). There is very little detailed information available on the Percy Lake body and detailed mapping would definitely help assess the mineral potential of this body.

Exposure

The extent of exposure is unknown since the area has not been mapped in any detail. The general topography of the area is suggestive of rocky terrain and exposure should be reasonably good.

Geochemistry

Fourteen analyses (unpublished data provided by C. Marmont, Geologist, MNDM Dorset) are listed in Table 44. These analyses may not represent the bulk

Table 44
Chemistry of the Percy Lake Anorthosite

%	88PMZ43	88PMZ46	88PMZ49	88CCM172	88CCM183	88PMZ37
SiO_2	53.62	48.16	50.91	52.07	52.24	52.51
Al_2O_3	27.97	30.37	29.40	29.16	27.56	28.78
Fe_2O_3	0.82	1.08	0.81	0.48	0.98	0.90
MgO	0.21	0.44	0.38	0.20	0.55	0.34
CaO	10.27	14.64	12.41	11.53	10.23	11.50
Na_2O	5.43	3.08	4.28	4.59	4.77	4.61
K_2O	0.63	0.27	0.66	0.73	1.16	0.83
TiO_2	0.08	0.08	0.07	0.08	0.09	0.09
P_2O_5	0.08	0.09	0.09	0.08	0.04	0.07
MnO	0.01	0.01	0.01	0.01	0.02	0.01
BaO	0.01	0.01	0.01	0.01	0.01	0.02
LOI	0.60	0.46	0.64	0.70	1.39	0.30
TOTAL	99.74	98.70	99.68	99.65	99.03	99.97
$CaO+Na_2O+K_2O$	16.33	17.98	17.35	16.85	16.16	16.94

All the above analyses are provided courtesy C. Marmont, Geologist, M.N.D.M., Dorset, Ontario.

Sample descriptions are not available, however all samples are assumed to be anorthosite.

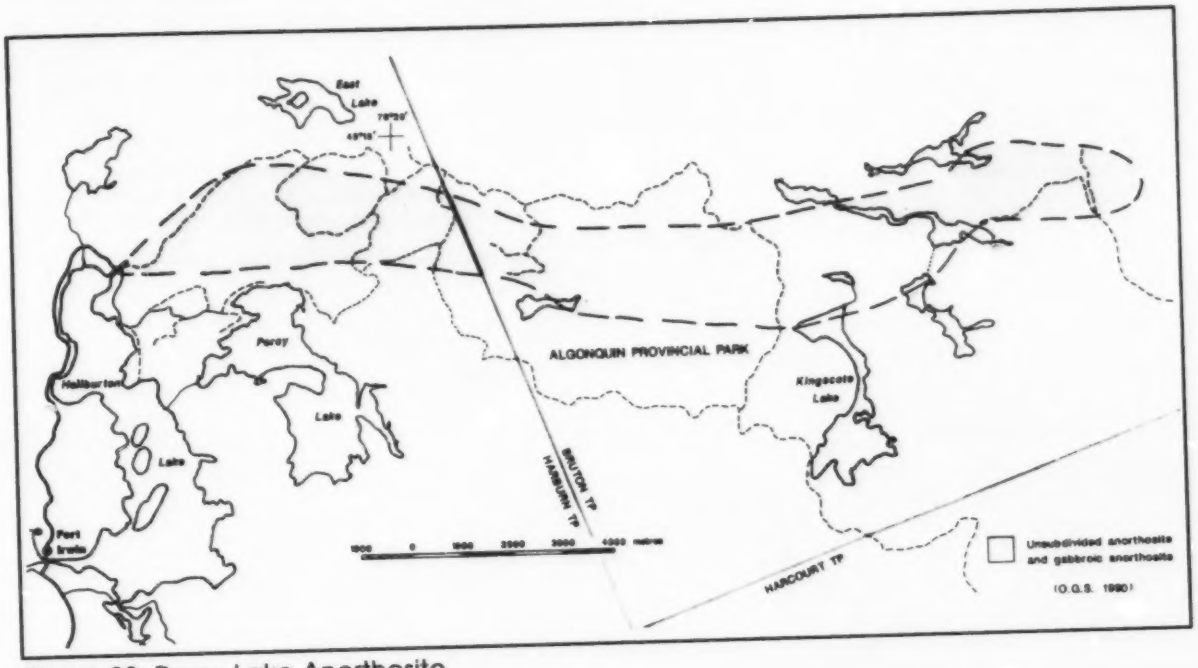


Figure 38. Percy Lake Anorthosite.

composition of the Percy Lake body, since sampling was at least in part concentrated in feldspar-rich areas. Average values for both Al_2O_3 and total alkali content are consistently high. Al_2O_3 averages 28.67 weight %. Total alkali content ranges from 15.43 weight % to 17.98 weight %, averaging 16.57 weight %.

Farquhar Lake Complex (31E/1)

The Farquhar Lake Complex consists of four bodies situated in Dudley Township, just north of Wilberforce (Figure 39) in Haliburton County. The combined areal extent of the complex is approximately 15 km^2. Of the four bodies, only two contain sufficient feldspar to be of interest to this study. These

88PMZ45	88PMZ48	88PMZ55	88PMZ171	88PMZ177	88PMZ179	88CCM22388CCM239	
52.79	55.13	51.84	52.32	51.58	53.03	53.02	52.53
28.84	27.06	29.61	29.43	27.28	28.85	28.95	28.10
0.73	0.98	0.53	0.89	2.64	0.63	0.42	0.55
0.55	0.68	0.14	0.54	1.79	0.31	0.25	0.33
10.30	9.57	11.81	11.57	10.63	10.48	10.39	9.81
4.56	5.03	4.56	4.50	4.42	4.93	4.67	4.83
1.67	0.83	0.73	0.74	1.06	0.90	0.98	1.41
0.11	0.10	0.12	0.15	0.16	0.08	0.06	0.05
0.05	0.07	0.07	0.08	0.07	0.06	0.06	0.03
0.01	0.02	0.01	0.01	0.04	0.01	0.01	0.20
0.01	0.01	0.04	0.01	0.01	0.02	0.02	0.04
1.00	0.77	0.75	0.61	0.77	0.75	0.90	1.91
100.65	100.25	100.25	100.85	100.45	100.50	99.74	99.80
16.53	15.43	17.10	16.81	16.11	16.31	16.04	16.05

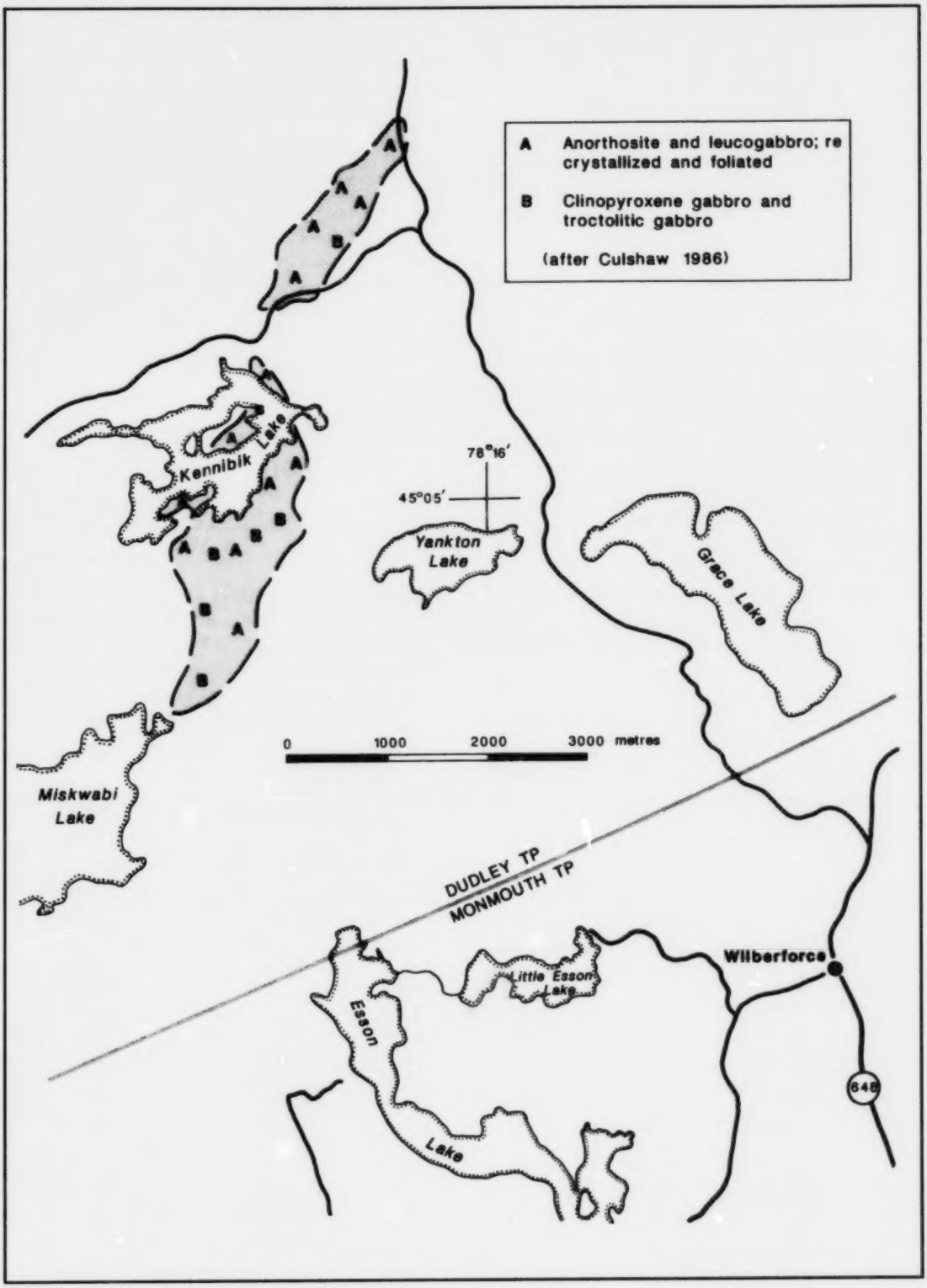


Figure 39. Farquhar Lake Complex.

two bodies can be accessed from Highway 648, 5 and 7 km north from Wilberforce.

Geology

The Farquhar Lake Complex lies within the Bancroft Terrane of the Central Metasedimentary Belt Boundary Zone. The two anorthositic bodies are elongate, roughly lens shaped and follow a northeast trend.

The two bodies have somewhat variable compositions. Anorthosite predominates in both, but leucogabbro is common. The bodies also contain clinopyroxene-gabbro and troctolitic gabbro, in the form of rounded inclusions which reach several metres in size (Culshaw 1986). The gabbro inclusions reduce the bulk feldspar content and therefore, inclusion density will be an important factor in assessing industrial mineral potential.

Culshaw (1986) provides a detailed description of the anorthosite. It is a white to grey, lineated, augen anorthosite gneiss. Plagioclase compositions are characteristically labradorite (An_{64}). Petrographic inspection of the anorthosite reveals recrystallized, fine grained, equigranular plagioclase surrounding larger, relict plagioclase augens. Mafic minerals occur interstitially to plagioclase. Pyroxene is replaced almost entirely by pale green amphibole, plus minor biotite. Meta-anorthosite occurs locally where scapolite replaces up to 20% of the plagioclase.

Economic Aspects

There are no mineral occurrences indicated on Culshaw's map (1986) nor are there any record in the assessment files for Dudley Township.

Geochemistry

Analyses of four anorthosite, two gabbro and two pyroxenite samples (Culshaw 1986) are presented in Table 45. Al_2O_3 values in the anorthosite are consistently over 25% Total alkali content for the anorthosites averages 15.87%.

Table 45
Chemistry of the Farquhar Lake Complex

	A	B	C	D	E	F	G	H
SiO_2	48.40	48.30	46.80	47.90	47.30	47.00	47.30	49.00
Al_2O_3	25.80	28.70	25.40	25.40	17.90	17.40	6.29	3.50
FeO (T)	2.72	1.13	2.98	2.70	6.91	7.32	9.09	6.25
MgO	2.46	1.53	3.92	2.90	8.23	8.95	14.80	17.90
CaO	12.20	11.90	11.90	11.90	11.90	11.80	16.20	17.50
Na_2O	2.96	3.11	3.14	3.34	2.30	2.48	0.97	0.28
K_2O	0.67	1.01	0.64	0.70	0.62	0.60	0.46	0.26
TiO_2	0.31	0.07	0.21	0.19	0.42	0.50	0.84	0.30
P_2O_5	0.03	0.01	0.02	0.04	0.30	0.03	0.02	0.02
MnO	0.05	0.02	0.05	0.05	0.13	0.13	0.17	0.13
H_2O	1.31	1.31	1.77	1.54	1.23	1.54	1.23	1.92
$CaO+Na_2O+K_2O$	15.83	16.02	15.68	15.94	14.82	14.88	17.63	18.04
C	-	0.92	-	-	-	-	-	- .
OR	4.15	6.04	3.98	4.34	3.80	3.89	2.84	1.62
AB	26.20	28.82	21.37	24.10	19.40	17.37	3.93	2.49
An	57.67	61.57	56.10	53.87	38.30	35.94	11.95	7.91
Me	-	0.90	3.56	3.97	0.49	2.40	-	- .
Di	2.70	-	3.25	4.40	12.38	13.37	41.92	54.36
Me	1.76	-	1.52	2.31	5.70	6.70	15.98	11.93
En	0.54	-	-	-	-	-	-	4.67
Fs	0.41	-	-	-	-	-	-	1.18
Fo	3.24	2.79	6.14	3.40	10.98	11.89	13.33	11.90
FA	2.66	1.61	3.62	2.90	7.22	7.57	6.42	3.30
Il	0.62	0.14	0.42	0.38	0.83	0.99	1.07	0.60
Ap	0.07	0.02	0.05	0.10	0.07	0.07	0.05	0.05

A : Anorthosite B : Anorthosite C : Anorthosite D : Anorthosite
E : Gabbro F : Gabbro G : Pyroxenite H : Pyroxenite

(Culshaw 1986)

Exposure

From Culshaw's map (1986) the exposure is consistent, although only approximately 5% of the body is indicated as outcrop. Presumably some outcrops are not indicated. The body appears to be particularly well exposed along the shores of Kennibik Lake. The more northerly of the two anorthositic bodies is well exposed where a road crosses the south end of the body.

Elzevir Terrane Anorthosites

The Elbow Lake Anorthosite (Figure 40) lies at the northeast end of the Elzevir Terrane, but has not been studied in detail. The anorthosite body is associated with locally abundant tonalite and intrudes Middle Proterozoic supracrustal rocks of the Grenville Supergroup (Easton, personal communication). It is highly strained and recrystallized by regional metamorphism. This body is the only known anorthosite occurrence of the Elzevir Terrane.

Sharbot Lake Terrane

The Wilkinson Anorthosite (Figure 41) is situated at the southwest end of the terrane, and lies within a large granodiorite body. It is possible that the Wilkinson Anorthosite is a large xenolith, related to the Mountain Grove Complex further to the northeast, which contains a significant anorthosite component. The Mountain Grove Complex was excluded from this study since the large gabbro component classified it as a secondary target.

Elbow Lake Anorthosite (31F/7)

The Elbow Lake Anorthosite (Figure 40) straddles the Madawaska River, southwest of Calabogie Lake in Blithfield Township. The body can be reached via Highway 508, 35 km southeast of Arnprior. The areal extent is approximately 12 km^2. Exposures are accessible by boat (shoreline of Madawaska River) and by foot along powerlines. This body has not been studied in any detail.

Geology

The Elbow Lake body occurs in the northeast part of the Elzevir Terrane in the Grenville Province. Anorthosite predominates, however minor gabbroic anorthosite is also present (Lumbers 1982). The extent of the less feldspathic gabbroic anorthosite must be determined to evaluate Al_2O_3 potential.

The anorthosite contains plagioclase of labradorite composition (An_{50-70}), 0 to 10% biotite and/or amphibole, and scapolite (Lumbers 1982). Details regarding accessory minerals, alteration, grain size and mineral textures are not available, although high grade regional metamorphism and deformation have resulted in recrystallization and megascopic folds (Lumbers 1982).

Economic Aspects

There are no mineral occurrences indicated within the Elbow Lake body (Toronto Assessment File Records Office) although rusty schists are noted on the south shore of Madawaska River (Lumbers 1982). Iron mineralization, possibly in the form of pyrite, is usually the cause of these rusty zones, and it is possible that sulphides have been introduced to the anorthosite along shear zones.

Exposure

The Elbow Lake body appears to be well exposed, particularly along the shores of Madawaska River. Mapping suggests approximately 75% exposure (Lumbers 1979).

Geochemistry

There is no geochemical data available on the Elbow Lake body. High-feldspar mineralogy and high metamorphic grade in the Elbow Anorthosite may be indicative of high Al_2O_3 potential.

Wilkinson Anorthosite (31C/10)

The Wilkinson Anorthosite (Figure 41) is located in Hinchbrooke Township in the Bedford Area. The body is accessible approximately 30 km east of Highway 38, from the Canadian Pacific Railway, which transects the anorthosite from the southwest. The Wilkinson Anorthosite is also exposed along the shores of Fish Lake. The areal extent of the anorthosite approximates only 1 km^2.

Geology

The Wilkinson Anorthosite is a small oval body in the Sharbot Lake Terrane of the Grenville Province. The body is lithologically zoned with an anorthosite core, and margins that are gradational into syenite (Harrison 1944). The anorthosite consists of very coarse grained plagioclase and a fine grained, mafic matrix. Plagioclase crystals 2.5 to 8.0 cm in length are common and crystals up to 30 cm in length are reported (Harding 1947). Protoclastic to cataclastic textures occur locally within the anorthosite and there is a general fining towards the margins (Harrison 1944). Augite and hypersthene are common accessory minerals, occasionally rimmed with actinolite, hornblende and biotite (Harrison 1944; Harding 1947). Titaniferous magnetite and apatite are present as accessories in all facies and sphene is a common accessory in the gabbroic phases (Harrison 1944). The Wilkinson body is also corundum-bearing in places (Harrison 1944).

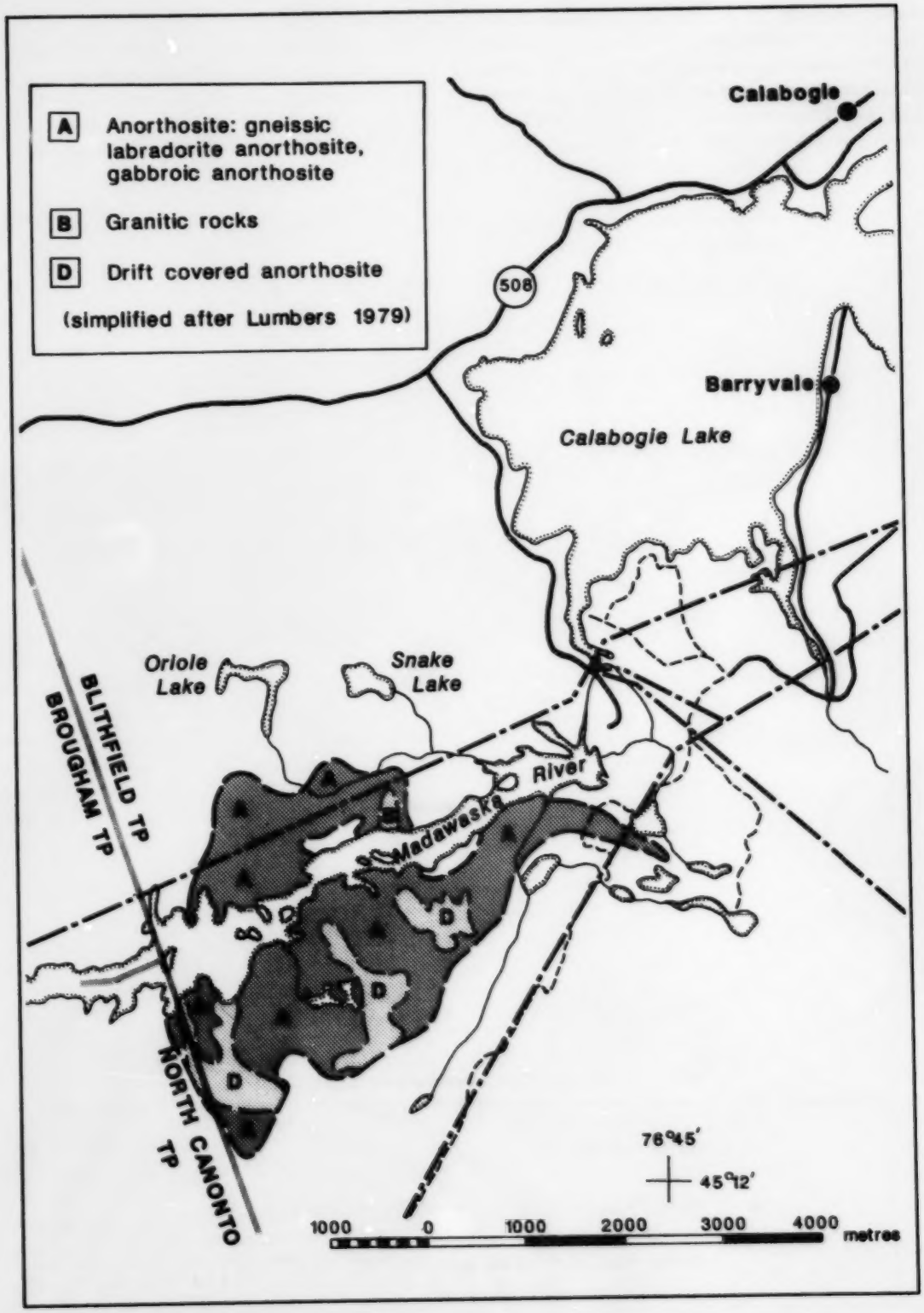


Figure 40. Elbow Lake Anorthosite.

Economic Aspects

There are no known mineral occurrences in the Wilkinson body (Assessment Files Research Office) with the exception of the nearby brucite occurrence (Figure 41). There have not been any correlations between the anorthosite body and the brucite occurrence.

Exposure

The anorthosite core of the Wilkinson body is well exposed in the vicinity of Wilkinson Station (Harrison 1944). Harding reports good exposure along the Wilkinson-Wagerville road. Judging from Harrison's map (1944) about 30% of the body is exposed.

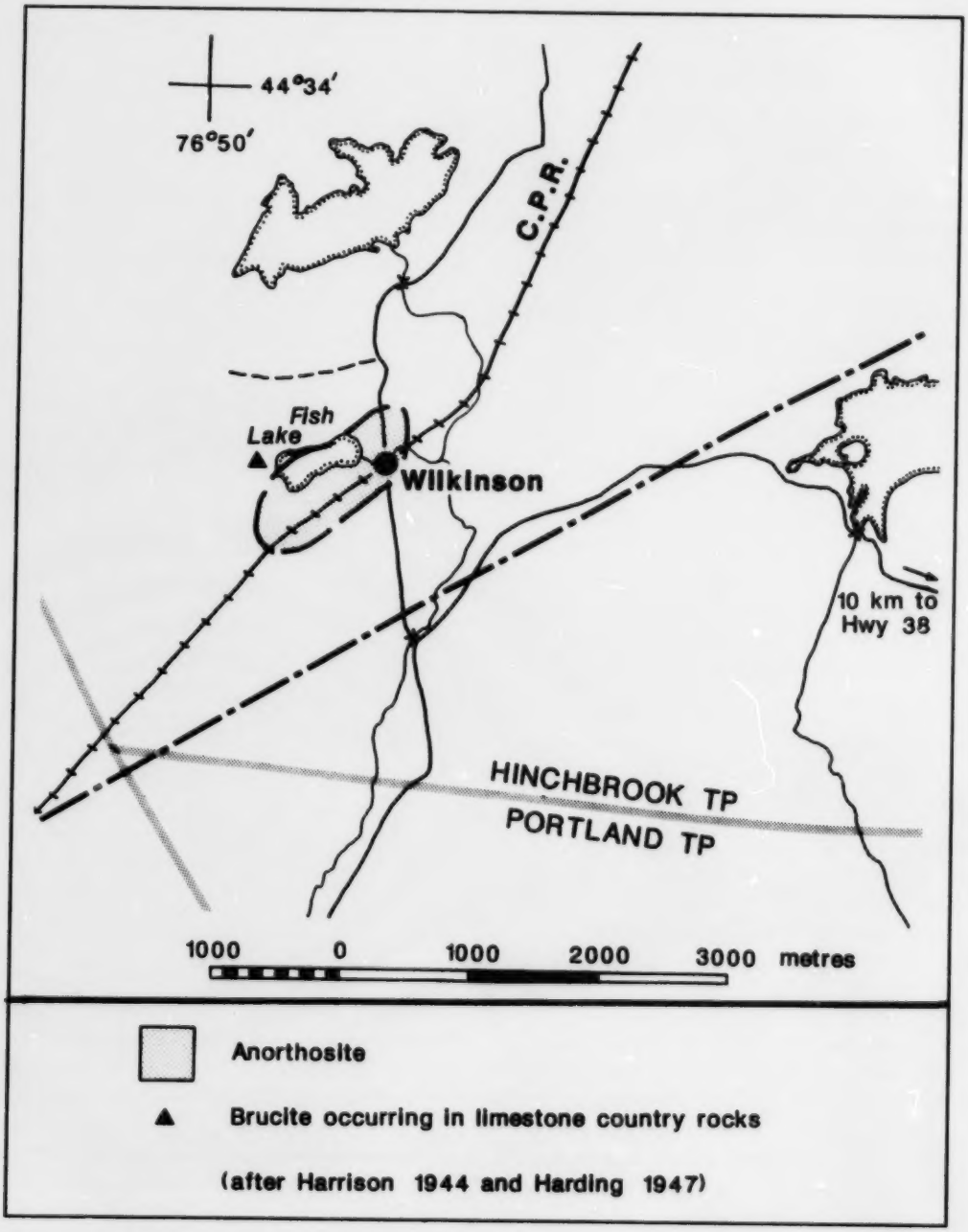


Figure 41. Wilkinson Anorthosite.

Table 46
Chemistry of the Wilkinson Anorthosite

wt.%	A	B
SiO_2	55.29	45.12
Al_2O_3	26.02	17.60
Fe_2O_3	1.60	4.77
FeO	1.30	7.29
MgO	0.28	6.05
CaO	8.63	11.71
Na_2O	5.71	2.66
K_2O	1.03	0.49
H_2O+	0.13	0.53
H_2O-	0.10	0.10
CO_2	0.07	0.56
TiO_2	0.52	2.24
P_2O_5	0.03	0.08
MnO	-	0.08
FeS_2	0.05	0.79
TOTAL	100.76	100.07
$CaO+Na_2O+K_2O$	15.37	14.86
Modes:	-	-
Quartz	-	-
Orthoclase	5.34	-
Albite	48.27	20.96
Anorthite	43.17	25.07
Hypersthene	-	6.25
Diopside	-	18.75
Actinolite	-	3.39
Hornblende	-	3.10
Biotite	1.14	3.66
Sericite	-	0.79
Scapolite	-	1.25
Calcite	0.16	1.20
Sphene	-	0.59
Magnetite	2.32	6.89
Ilmenite	0.99	3.79
Corundum	-	1.64
Pyrite	0.05	0.79
Apatite	0.06	0.19
Kaolin	-	1.54
Total	101.50	99.85
Plagioclase	An_{32-45}	An_{53}
Mafics	4.50	47.21

A : An average of three samples taken from the central portion of the Wilkinson anorthosite
B : "Gabbroic rock near northeast border of Wilkinson anorthosite" (Harrison 1944).

Geochemistry

Table 46 contains chemical and modal analyses of anorthosite and gabbroic anorthosites from the Wilkinson body. Modal analyses indicate that the typical anorthosite contains 90% or more feldspar and an average Al_2O_3 value for three anorthosite samples is 26.02 weight %. The total alkali content for anorthosite and gabbroic samples averages 15.12%.

Although the Wilkinson body is very small, it is well exposed, has good access and is within 40 km of Kingston.

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